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(54) Title: ILLUMINATION SYSTEM WITH OPTICAL INTEGRATOR FOR AN IMAGE PROJECTOR

(57) Abstract: Apparatus for providing light is disclosed. The apparatus comprises a light source having a light emitting surface for generating a light beam, and at least one linear focusing element defining a longitudinal optical axis. The linear focusing element forms different linear foci at different longitudinal locations along the longitudinal optical axis. The apparatus is particularly useful as an image generating apparatus in a system which provides different linear expansion ratios in different transverse dimensions.

APPARATUS, METHOD AND SYSTEM FOR PROVIDING LIGHT

FIELD AND BACKGROUND OF THE INVENTION

The present invention relates to optics and, more particularly, to apparatus, method and system for providing light such as to form different linear foci at different longitudinal locations.

Miniaturization of electronic devices has always been a continuing objective in the field of electronics. Electronic devices are often equipped with some form of a display, which is visible to a user. As these devices reduce in size, there is an increase need for manufacturing compact displays, which are compatible with small size electronic devices. Besides having small dimensions, such displays should not sacrifice image quality, and be available at low cost. By definition the above characteristics are conflicting and many attempts have been made to provide some balanced solution.

An electronic display may provide a real image, the size of which is determined by the physical size of the display device, or a virtual image, the size of which may extend the dimensions of the display device.

A real image is defined as an image, projected on or displayed by a viewing surface positioned at the location of the image, and observed by an unaided human eye (to the extent that the viewer does not require corrective glasses). Examples of real image displays include a cathode ray tube (CRT), a liquid crystal display (LCD), an organic light emitting diode array (OLED), or any screen-projected displays. A real image could be viewed normally from a distance of about at least 25 cm, the minimal distance at which the human eye can utilize focus onto an object. Unless a person is long-sighted, he may not be able to view a sharp image at a closer distance.

Typically, desktop computer systems and workplace computing equipment utilize CRT display screens to display images for a user. The CRT displays are heavy, bulky and not easily miniaturized. For a laptop, a notebook, or a palm computer, flat-panel display is typically used. The flat-panel display may use LCD technology implemented as passive matrix or active matrix panel. The passive matrix LCD panel consists of a grid of horizontal and vertical wires. Each intersection of the grid constitutes a single pixel, and controls an LCD element. The LCD element either

allows light through or blocks the light. The active matrix panel uses a transistor to control each pixel, and is more expensive.

An OLED flat panel display is an array of light emitting diodes, made of organic polymeric materials. Existing OLED flat panel displays are based on both passive and active configurations. Unlike the LCD display, which controls light transmission or reflection, an OLED display emits light, the intensity of which is controlled by the electrical bias applied thereto. Flat-panels are also used for miniature image display systems because of their compactness and energy efficiency compared to the CRT displays. Small size real image displays have a relatively small surface area on which to present a real image, thus have limited capability for providing sufficient information to the user. In other words, because of the limited resolution of the human eye, the amount of details resolved from a small size real image might be insufficient.

By contrast to a real image, a virtual image is defined as an image, which is not projected onto or emitted from a viewing surface, and no light ray connects the image and an observer. A virtual image can only be seen through an optic element, for example a typical virtual image can be obtained from an object placed in front of a converging lens, between the lens and its focal point. Light rays, which are reflected from an individual point on the object, diverge when passing through the lens, thus no two rays share two endpoints. An observer, viewing from the other side of the lens would perceive an image, which is located behind the object, hence enlarged. A virtual image of an object, positioned at the focal plane of a lens, is said to be projected to infinity. A virtual image display system, which includes a miniature display panel and a lens, can enable viewing of a small size, but high content display, from a distance much smaller than 25 cm. Such a display system can provide a viewing capability which is equivalent to a high content, large size real image display system, viewed from much larger distance.

Conventional virtual image displays are known to have many shortcomings. For example, such displays have suffered from being too heavy for comfortable use, as well as too large so as to be obtrusive, distracting and even disorienting. These defects stem from, *inter alia*, the incorporation of relatively large optics systems within the mounting structures, as well as physical designs which fail to adequately take into account important factors as size, shape, weight, *etc.*

Recently, holographic optical elements have been used in portable virtual image displays. Holographic optical elements serve as an imaging lens and a combiner where a two-dimensional, quasi-monochromatic display is imaged to infinity and reflected into the eye of an observer. A common problem to all types of holographic optical elements is their relatively high chromatic dispersion. This is a major drawback in applications where the light source is not purely monochromatic. Another drawback of some of these displays is the lack of coherence between the geometry of the image and the geometry of the holographic optical element, which causes aberrations in the image array that decrease the image quality.

New designs, which typically deal with a single holographic optical element, compensate for the geometric and chromatic aberrations by using non-spherical waves rather than simple spherical waves for recording; however, they do not overcome the chromatic dispersion problem. Moreover, with these designs, the overall optical systems are usually very complicated and difficult to manufacture. Furthermore, the field-of-view resulting from these designs is usually very small.

U.S. Patent No. 4,711,512 to Upatnieks describes a diffractive planar optics head-up display configured to transmit collimated light wavefronts of an image, as well as to allow light rays coming through the aircraft windscreen to pass and be viewed by the pilot. The light wavefronts enter an elongated optical element located within the aircraft cockpit through a first diffractive element, are diffracted into total internal reflection within the optical element, and are diffracted out of the optical element by means of a second diffractive element into the direction of the pilot's eye while retaining the collimation. Upatnieks, however, does not teach how to transmit a wide field-of-view through the display, or how to transmit a broad spectrum of wavelengths (for providing color images). A major limitation of the head-up display of Upatnieks is the use of thick volume holograms which, albeit their relatively high diffraction efficiency, are known to have narrow angular and chromatic response.

U.S. Patent Nos. 5,966,223 and 5,682,255 to Friesem *et al.* describes a holographic optical device similar to that of Upatnieks, with the additional aspect that the first diffractive optical element acts further as the collimating element that collimates the waves emitted by each data point in a display source and corrects for field aberrations over the entire field-of-view. The field-of-view discussed is $\pm 6^{\circ}$, and there is a further discussion of low chromatic sensitivity over wavelength shift of $\Delta\lambda_c$

of ±2 nm around a center wavelength λ_c of 632.8 nm. However, the diffractive collimating element of Friesem *et al.* is known to narrow spectral response, and the low chromatic sensitivity at spectral range of ±2 nm becomes an unacceptable sensitivity at ±20 nm or ±70 nm.

U.S. Patent No. 6,757,105 to Niv *et al.*, the contents of which are hereby incorporated by reference, provides a diffractive optical element for optimizing a field-of-view for a multicolor spectrum. The optical element includes a light-transmissive substrate and a linear grating formed therein. Niv *et al.* teach how to select the pitch of the linear grating and the refraction index of the light-transmissive substrate so as to trap a light beam having a predetermined spectrum and characterized by a predetermined field of view to propagate within the light-transmissive substrate via total internal reflection. Niv *et al.* also disclose an optical device incorporating the aforementioned diffractive optical element for transmitting light in general and images in particular into the eye of the user.

The above virtual image devices, however, provide a single optical channel, hence allowing the scene of interest to be viewed by one eye. It is recognized that the ability of any virtual image devices to transmit an image without distortions inherently depends on whether or not light rays emanating from all points of the image are successfully transmitted to the eye of the user in their original color. Due to the single optical channel employed by presently known devices, the filed-of-view which can be achieved without distortions or loss of information is rather limited.

A binocular device which employs several diffractive optical elements is disclosed in U.S. Patent Application Nos. 10/896,865 and 11/017,920, and in International Patent Application, Publication No. WO 2006/008734, the contents of which are hereby incorporated by reference. An optical relay is formed of a light transmissive substrate, an input diffractive optical element and two output diffractive optical elements. Collimated light is diffracted into the optical relay by the input diffractive optical element, propagates in the substrate via total internal reflection and coupled out of the optical relay by two output diffractive optical elements. The input and output diffractive optical elements preserve relative angles of the light rays to allow transmission of images with minimal or no distortions. The output elements are spaced apart such that light diffracted by one element is directed to one eye of the viewer and light diffracted by the other element is directed to the other eye of the

viewer. The binocular design of these references significantly improves the field-of-view.

Generally, virtual image display systems, such as those described above, include a certain type of image generating apparatus which produce the image being viewed. The apparatus typically projects a light beam constituting the image on an optical relay device which in turn ensures divergence of light rays so as to form the virtual image. Such apparatus typically includes a passive or active miniature display device. Passive display devices include LCD, electrochemical display (ECD), electrophoretic image display (EPID) and digital light processor (DLP). Active display devices include CRT, plasma display panel (PDP), OLED array and electroluminescent display (ELD). In active display devices, each pixel radiates light independently. Passive display devices, on the other hand, do not produce light within the pixel and the pixel is only able to block transmission of light generated by a backlight assembly, or alternatively enable reflection of light generated by a front illumination assembly.

Several types of backlight assemblies are known. Generally, the backlight illumination generated can be white or it can be polychromatic, depending on the type of passive display device. Backlight assemblies which employ white illumination include a white light source and color filters such as a color wheel or an arrangement of red, green and blue (RGB) filters at each pixel of the display. Backlight assemblies which employ polychromatic light may operate in a color sequential operation or they can have three separate illumination sources.

Irrespectively of the mechanism used to generate the image, virtual image display systems employ condenser lens to form a real image of the miniature display device on a projection lens. Typically, the clear aperture of the projection lens is larger than the area of the miniature display to allow placing the miniature display adjacent to the condenser lens hence to improve light transmission. However, even with such configurations, the efficiency is far from being optimal and a significant amount of stray light is produced.

There is thus a widely recognized need for, and it would be highly advantageous to have apparatus, method and system for providing light devoid of the above limitations.

SUMMARY OF THE INVENTION

According to one aspect of the present invention there is provided an apparatus for providing light. The comprises a light source having a light emitting surface for generating a light beam, a passive modulator configured to modulate the light beam to constitute an image therein; and at least one linear focusing element. The linear focusing element defines a longitudinal optical axis of the apparatus and forms different linear foci at different longitudinal locations along the longitudinal optical axis.

According to further features in preferred embodiments of the invention described below, the linear focusing element forms two foci: a first linear focus with respect to a first transverse dimension at a first longitudinal location, and a second linear focus with respect to a second transverse dimension at a second longitudinal location.

According to still further features in the described preferred embodiments the apparatus the linear focusing element comprises a first arrangement of lenses characterized by spherical symmetry, and a second arrangement of lenses characterized by a symmetry other than spherical symmetry. According to still further features in the described preferred embodiments the second arrangement of lenses is characterized by a cylindrical symmetry.

According to still further features in the described preferred embodiments the first location is at a distance Z_1 from the light source and the second location is at a distance Z_2 from the light source, wherein the ratio between Z_2 and Z_1 is at least 2, more preferably 3.

According to another aspect of the present invention there is provided apparatus for providing light. The apparatus comprises: a light source having a light emitting surface for generating a light beam; a passive modulator configured to modulate the light beam to constitute an image therein; and one or more linear focusing elements defining a longitudinal optical axis. The linear focusing element has a first arrangement of lenses characterized by spherical symmetry and a second arrangement of lenses characterized by a symmetry other than spherical symmetry, *e.g.*, cylindrical symmetry.

According to yet another aspect of the present invention there is provided a method of providing light. The method comprises the apparatus described herein.

According to further features in preferred embodiments of the invention described below, the apparatus further comprises an optical projection element interposed in the light path of the light beam and configured for projecting the light beam in a collimated manner.

According to still another aspect of the present invention there is provided a system for providing an image to a user. The system comprises: the apparatus described herein and an optical relay device. The apparatus serves as image generating apparatus, and the optical relay device relays the light beam provided by the apparatus in a manner such that the light beam is expanded in a first transverse dimension and relayed to occupy at least one predetermined two-dimensional eye-box region in space.

According to further features in preferred embodiments of the invention described below, the first longitudinal location is defined at the location of the projection optical element, and the second longitudinal location is defined at the eye-box region.

According to an additional aspect of the present invention there is provided a method of viewing an image, comprising operating the system described herein.

According to further features in preferred embodiments of the invention described below, the linear focusing element is designed and constructed such as to form an intermediate virtual image of a first linear segment of the light emitting surface. According to still further features in the described preferred embodiments the linear focusing element also forms a real image of the intermediate virtual image at the first longitudinal location.

According to still further features in the described preferred embodiments the linear focusing element is designed and constructed such as to form an intermediate virtual image of a second linear segment of the light emitting surface. According to still further features in the described preferred embodiments the projection optical element is designed and constructed such as to form real image of the intermediate virtual image at the second longitudinal location.

According to still further features in the described preferred embodiments the first linear focus is formed at a first transverse plane being at the first longitudinal location, wherein any point on the first transverse plane other than points belonging to the first linear focus is out of focus with respect to the light emitting surface.

According to still further features in the described preferred embodiments the second linear focus is formed at a second transverse plane being at the second longitudinal location, and wherein any point on the second transverse plane other than points belonging to the second linear focus is out of focus with respect to the light emitting surface.

According to still further features in the described preferred embodiments the optical relay device comprises a light transmissive substrate formed with at least one input optical element for coupling the light beam into the light transmissive substrate, and at least one output optical element for expanding the light beam in the first transverse dimension and coupling the light beam out of the light transmissive substrate to the two-dimensional region.

According to still further features in the described preferred embodiments the at least one input optical element and/or the at least one output optical element comprise diffractive optical elements.

According to still further features in the described preferred embodiments the at least one linear focusing element comprises a first arrangement of lenses characterized by spherical symmetry and a second arrangement of lenses characterized by a symmetry other than spherical symmetry.

According to still further features in the described preferred embodiments the optical relay device comprises an input diffractive optical element, a first output diffractive optical element and a second output diffractive optical element.

According to still further features in the described preferred embodiments the input diffractive optical element is designed and constructed for diffracting the light beam to propagate within the light-transmissive substrate via total internal reflection; the first output diffractive optical element is designed and constructed for diffracting light corresponding to a first part of the image out of the light-transmissive substrate; and the second output diffractive optical element is designed and constructed for diffracting light corresponding to a second part of the image out of the light-transmissive substrate, such that the combination of the first and the second part substantially reconstructs the image.

According to still further features in the described preferred embodiments each of the at least one input optical element and the at least one output optical element is characterized by planar dimensions defined by a length along the first transverse

dimension and a width along the second transverse direction, wherein a width of the at least one output optical element is smaller than a width of the at least one input optical element.

According to still further features in the described preferred embodiments the linear focusing element is characterized by a first effective focal length in the first transverse dimension and a second effective focal length in the second transverse dimension, the second effective focal length being longer than the first effective focal length.

According to still further features in the described preferred embodiments the at least one linear focusing element is a lenslet array.

According to still further features in the described preferred embodiments the lenslet array has a first side and a second side opposite the first side, wherein the first arrangement of lenses is an array of spherical lenses arranged on the first side, and wherein the second arrangement of lenses is array of cylindrical lenses arranged on the second side.

According to still further features in the described preferred embodiments at least one of the array of cylindrical lenses and the array of spherical lenses is corrugated so as to impart a substantially homogenous intensity distribution across the light beam.

According to still further features in the described preferred embodiments the lenslet array is made, at least in part, of a diffractive material.

According to still further features in the described preferred embodiments linear focusing element comprises at least one element selected from the group consisting of a condenser lens system, a Fresnel zone plate and a holographic lens.

According to still further features in the described preferred embodiments the apparatus further comprises a beam homogenizer interposed in the optical path of the light beam for imparting a substantially homogenous intensity distribution across the light beam.

The present invention successfully addresses the shortcomings of the presently known configurations by providing apparatus, method and system for providing light.

Unless otherwise defined, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs. Although methods and materials similar or equivalent to those

described herein can be used in the practice or testing of the present invention, suitable methods and materials are described below. In case of conflict, the patent specification, including definitions, will control. In addition, the materials, methods, and examples are illustrative only and not intended to be limiting.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention is herein described, by way of example only, with reference to the accompanying drawings. With specific reference now to the drawings in detail, it is stressed that the particulars shown are by way of example and for purposes of illustrative discussion of the preferred embodiments of the present invention only, and are presented in the cause of providing what is believed to be the most useful and readily understood description of the principles and conceptual aspects of the invention. In this regard, no attempt is made to show structural details of the invention in more detail than is necessary for a fundamental understanding of the invention, the description taken with the drawings making apparent to those skilled in the art how the several forms of the invention may be embodied in practice.

In the drawings:

FIGs. 1a-b are schematic illustrations of cross-sectional views of an apparatus for providing light, according to various exemplary embodiments of the present invention;

FIGs. 1c-e are schematic illustrations depicting in perspective manner the operation of a linear focusing element, according to various exemplary embodiments of the present invention;

FIG. 2a is a schematic illustration of a cross-sectional view of a light source according to various exemplary embodiments of the present invention;

FIG. 2b is a schematic illustration of a cross-sectional view of an optical passive modulator according to various exemplary embodiments of the present invention;

FIGs. 3a-b are schematic illustrations of the linear focusing element in a preferred embodiment in which a lenslet array is employed;

FIG. 4 is a schematic cross-sectional illustration of a system for providing an image to a user, according to various exemplary embodiments of the present invention;

FIGs. 5a-b are schematic illustrations exemplifying ray tracing within the system, according to various exemplary embodiments of the present invention;

FIGs. 6a-b are fragmentary schematic illustrations depicting realization of the ray tracing shown in Figures 5a-b;

FIG. 7 is a schematic illustration of light diffraction by a linear diffraction grating operating in transmission mode;

FIGs. 8a-c are schematic illustrations of cross sectional views of an optical relay device according to various exemplary embodiments of the invention;

FIG. 8d is a schematic illustration of a rectangular field-of-view of the optical relay device, according to various exemplary embodiments of the invention;

FIGs. 8e-f are schematic illustrations of field-of-view angles of the optical relay device, according to various exemplary embodiments of the invention;

FIGs. 9a-b are schematic illustrations of a perspective view (Figure 3a) and a side view (Figure 3b) of the optical relay device, in a preferred embodiment in which the device comprises one input optical element and two output optical elements, according to various exemplary embodiments of the present invention;

FIGs. 10a-b are fragmentary views schematically illustrating wavefront propagation within the optical relay device, according to preferred embodiments of the present invention; and

FIG. 11 is a schematic illustration of binocular system, in the preferred embodiment in which the diffraction phenomenon is used for relaying the light.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present embodiments comprise apparatus and method which can be used for providing light. Specifically, but not exclusively, the present embodiments can be used for generating and transmitting an image to an optical relay of a virtual image display system. The present embodiments further comprise a system which employs the apparatus and which can be used for viewing a virtual image. The present embodiments can be used in many applications in which virtual images are viewed, including, without limitation, eyeglasses, binoculars, head mounted displays, head-up displays, cellular telephones, personal digital assistants, aircraft cockpits and the like.

The principles and operation of a device and system according to the present invention may be better understood with reference to the drawings and accompanying descriptions.

Before explaining at least one embodiment of the invention in detail, it is to be understood that the invention is not limited in its application to the details of construction and the arrangement of the components set forth in the following description or illustrated in the drawings. The invention is capable of other embodiments or of being practiced or carried out in various ways. Also, it is to be understood that the phraseology and terminology employed herein is for the purpose of description and should not be regarded as limiting.

Reference is now made to Figures 1a-b, which are schematic illustrations of cross-sectional views of an apparatus **100** for providing light, according to various exemplary embodiments of the present invention. Apparatus **100** is illustrated in Figures 1a-b and described below with reference to *x-y-z* Cartesian coordinate system, where Figure 1a provides a schematic cross-sectional view of apparatus **100** in the *x-z* plane and Figure 1b provides a schematic cross-sectional view of apparatus **100** in the *y-z* plane. These cross-sectional views are referred to herein as a "side view" (*x-z* plane, Figure 1a) and a "top view" (*y-z* plane, Figure 1b).

In its simplest configuration, apparatus **100** comprises a light source **102** having a light emitting surface **103** for generating a light beam **104**, and one or more linear focusing elements **106** which provide linear foci as further detailed hereinbelow. Light source **102** is aligned with linear focusing element **106** such that element **106** is in the optical path of beam **104** or a portion thereof.

Linear focusing element **106** has a longitudinal optical axis **108** which, without the loss of generality, is aligned with the *z* axis. The terms "*z* axis" and "longitudinal axis" will therefore be used below interchangeably. Additionally, since in the presented coordinate system both the *x* axis and the *y* axis are perpendicular to the longitudinal axis, each of the *x* and *y* axes is referred to as a "transverse axis", any linear measure (length) parallel to one of these axis is referred to as a transverse dimension, and any plane parallel to the *x-y* plane is referred to as a "transverse plane". The two transverse dimensions are distinguished by the terms "horizontal" for a transverse dimension which is parallel to the *y* axis, and "vertical" for a transverse dimension which is parallel to the *x* axis. Using this terminology, a plane parallel to

the x-z plane is referred to below as a "vertical plane" and a plane parallel to the y-z plane is referred to below as a "horizontal plane." As will be appreciated by one of ordinary skill in the art, this terminology describes a situation in which the x axis is directed upwards, but it is not intended to limit the scope of present invention, to any specific orientation of apparatus **100** in space.

In various exemplary embodiments of the invention apparatus **100** is used as an image generating apparatus. In these preferred embodiments, light beam **104** is modulated according to image data to constitute an image therein. The modulation of light **104** is preferably by a passive modulator **110**. Thus, light source **102** serves as a component in a passive display device, which may be a transmissive passive display device, a reflective passive display device or a transflective passive display device. When a transmissive passive display device is employed modulator **110** is a transmissive passive display panel and light source provides backlight illumination, when a reflective passive display device is employed modulator **110** is a reflective passive display panel and light source **102** provides frontlight illumination, and when transflective passive display device is employed modulator **110** is a transflective passive display panel light source **102** provides backlight and/or frontlight illumination.

As used herein, "passive display panel" refers to any pixelated panel in which the pixels do not produce light and which requires backlight or frontlight for operation. Representative examples of transmissive passive display panels include, without limitation, a transmissive liquid crystal panel and electrophoretic panel. Representative examples of reflective passive display panels include, without limitation, a reflective liquid crystal panel (Liquid Crystal on Silicon or LCOS), and Digital Light Processor (DLP™) panel. In various exemplary embodiments of the invention the passive display panel is a liquid crystal panel.

A schematic cross-sectional view of light emitting surface **103** in the transverse plane according to various exemplary embodiments of the present invention is illustrated in Figure 2a. It the representative example of Figure 2a, light source **102** comprises a plurality of pixel regions **112** which are arranged over a grid **114** in a plurality of rows along the horizontal dimension and a plurality of columns along the vertical dimensions. But this need not necessarily be the case, since, for some applications, it may not be necessary for the light source to be pixilated. For example,

when light source **102** provides a non-modulated light (*e.g.*, for backlighting or for applications in which apparatus serves as illuminating apparatus) light source **102** can be provided as an illumination sheet or any other non pixilated single light source. Yet, from the standpoint of optical efficiency, the use of pixilated light source is favored for the generation of both modulated and non-modulated light beams.

Light source **102** can be embodied as a two-dimensional array of light emitting diodes which may be of any type known in the art, including inorganic light emitting diodes and organic light emitting diodes. Preferably, the light emitting diodes are surrounded by reflectors so as to gather the light emitted from the semiconductor material and reflect it downstream the longitudinal axis.

Light source **102** preferably provides a light beam having a substantially homogenous intensity distribution thereacross. When light source **102** is a two-dimensional array of light emitting diodes, the diodes are selected with packaging which facilitate homogenous intensity distribution. Alternatively or additionally, apparatus **100** can comprise a beam homogenizer **126** interposed in the optical path of light beam **104** for imparting a substantially homogenous intensity distribution across beam **104**. Homogenizer **126** can be a diffusive panel, an opal plate, a corrugated plate, ground glass plate and the like.

Figure 2b is a schematic cross-sectional view in the transverse plane of modulator **110** in the preferred embodiment in which modulator **110** is an LCD panel. It the representative example of Figure 2b, modulator **110** comprises a plurality of pixel regions **116** arranged over a grid **118**. Each pixel region **116** is defined by two or more sub-pixel positions **120**. The sub-pixel positions correspond to the color channels characterizing the respective pixel region. Thus, a pixel region of two color channels has two pixel positions, a pixel region of three color channels (*e.g.*, RGB channels) has three pixel positions, *etc.*

When modulator **110** is an LCD panel, the pixel regions are typically formed of thin film transistors fabricated on a transparent substrate. Color filters (typically three per pixel region) are fabricated on another transparent substrate to produce colored light by transmitting one third of the light passing therethrough. A liquid crystal layer is sandwiched between the thin film transistors layer and the color filters layer. The optical properties of the liquid crystal in each pixel region are modulated by the thin film transistors to create a light intensity modulation across the area of the

panel. For example, a static polarizer can be used to polarize the light produced by the light source, and the liquid crystal pixels can selectively manipulate the polarization of the light passing therethrough. The light intensity modulation is achieved using a static polarizer positioned in front of the liquid crystal pixels which prevents transmission of light of certain polarization. The color filters colorize the intensity-modulated light emitted by the pixels to produce a color output. By selective opacity temporal modulation of neighboring pixels of the three color components, selected intensities of the three component colors are blended together to selectively control color light output. Selecting the blending of three primary colors such as RGB can generally produce a full range of colors suitable for color display purposes. All these designs and operations are well known to those ordinarily skilled in the art of display systems.

Referring again to figures 1a-b, linear focusing element **106** is preferably designed and constructed to form different linear foci at different longitudinal locations.

The term "linear focus" will be better understood with the following description.

In geometric optics, a real image of a two-dimensional object, *e.g.*, a light emitting surface or the like, is the locus of all points at which at least two light rays emanating from the same point (*e.g.*, a pixel) on the light emitting surface intersect. When the real image of the light emitting surface is a one dimensional locus (*e.g.*, a straight line) a linear focus is said to be created.

Thus, "linear focus" refers to a line, typically a straight line, which is composed of a plurality of points each defined by the intersection of at least two light rays originating from the same point of the light emitting surface.

Linear focusing element **106** forms a linear focus **124** with respect to the horizontal dimension at one location along axis **108**, denoted Z_1, and a linear focus **122** with respect to the vertical dimension at another location along axis **108**, denoted Z_2. In terms of geometric optics, focusing element **106** converges the light rays such that projections of the light rays on a horizontal plane are converged at location Z_1, and projections of the light rays on a vertical plane are converged at location Z_2.

The operation principles of focusing element **106** are schematically illustrated in Figures 1c-e. Shown in Figures 1c-e are perspective views of two linear segments

of light source **102**, one linear segment **102y** along the horizontal dimension and one linear segment **102x** along the vertical dimensions. Also shown are focusing element **106** and linear foci **122** and **124**. Segments **102y** and **102x** as well as foci **124** and **122** are illustrated in Figures 1c-e as arrows. Light rays emanating from segment **102y** are converged by focusing element **106** to form focus **124** on a transverse plane **144** located at location Z_1 and light rays emanating from segment **102y** are converged by element **106** to form focus **122** on a transverse plane **142** located at location Z_2. Thus, segment **102y** is imaged by element **106** on plane **144** and segment **102x** is imaged by element **106** on plane **142**.

In various exemplary embodiments of the invention segment **102y** is a row of pixel regions of light source **102** (see, *e.g.*, central row **136** in Figure 2a) or a part thereof, and segment **102x** is a column of pixel regions of light source **102** (see, *e.g.*, central column **138** in Figure 2a) or a portion thereof.

It is appreciated that light rays also emanate from parts of light source **102** which are other than the aforementioned segments **102y** and **102x**. These parts of the light source, however are not necessarily imaged on any of planes **142** and **144**. For example, light rays emanating from a pixel region being on a row other than row **136** and a column other than column **138** do not converge on any of planes **142** and **144**.

Thus, according to a preferred embodiment of the present invention any point on plane **144** other than the points forming focus **124** is out of focus with respect to the light emitting surface of source **102**. Similarly, any point on transverse plane **142** other than the points forming focus **122** is out of focus with respect to the light emitting surface.

Figure 1c illustrates both linear foci **122** and **124** along axis **108** and Figures 1d-e illustrate convergence of representative light rays emanating from the heads of the arrows illustrating segment **102y** (Figure 1d) and segment **102x** (Figure 1e). Specifically, Figure 1d exemplifies four light rays **104-1**, **104-2**, **104-3** and **104-4** emanating from the head of the arrow representing segment **102y** and converging on the transverse plane at location Z_1 the head of the arrow representing focus **124**, and Figure 1e exemplifies four light rays **104-5**, **104-6**, **104-7** and **104-8** emanating from the head of the arrow representing segment **102x** and on the transverse plane at location Z_2 the head of the arrow representing focus **122**.

Other light rays which emanate from other points of the segments converge on the respective transverse planes to form the linear foci. For example, light rays emanating from the tail of the arrow representing segment **102y** are converged by element **106** to form the tail of the arrow representing focus **124**. Similarly, light rays emanating from the tail of the arrow representing segment **102x** are converged by element **106** to form the tail of the arrow representing focus **122**. For the clarity of presentation, however, the additional light rays are not shown in Figure 1d-e, but one of ordinary skill in the art, provided with the details described herein would know how to draw such light rays.

In various exemplary embodiments of the invention the ratio Z_2/Z_1 is at least 2, more preferably at least 3.

Optionally and preferably apparatus **100** is supplemented with an optical projection element **44** which can be positioned at longitudinal location Z_1 in the optical path of the light beam. Projection element **44** is preferably employed when it is desired to place source **102** near element **106**, such that focusing element **106** forms a virtual image of segment **102x**, which virtual image is projected by element **106** to forms a real image of segment **102x** at plane Z_2. An exemplified ray tracing of this embodiment is provided in Figures 5a-b hereinunder.

Focusing element **106** can be embodied in more than one way. Typically, element **106** comprises arrangements of lenses which are constructed and aligned such that the effective focal length in the horizontal dimension differs from that the effective focal length in the vertical dimension. Preferably, the focal length in the vertical dimension is longer than the focal length in the horizontal dimension. A preferred difference between the focal lengths is of at least 20 %, more preferably at least 25 %.

One way to achieve different effective focal lengths is by a combination of lenses with different symmetry properties. Thus, according to a preferred embodiment of the present invention focusing element **106** comprises at least one arrangement of lenses which are characterized by spherical symmetry and at least one arrangement of lenses which are characterized by a symmetry other than spherical symmetry. The combination of spherical and non-spherical lenses results in the desired difference in effective focal length. The non-spherical lenses are optionally and preferably cylindrical lenses. Such non-spherical lenses are favored from the standpoints of

availability and design simplicity. Other non-spherical lenses are not excluded from the scope of the present invention.

Reference is now made to Figures 3a-b which are schematic illustrations of linear focusing element **106** in a preferred embodiment in which a lenslet array is employed. Figure 3a is a side view (parallel to the *x-z* plane) and Figure 3b is a top view (parallel to the *y-z* plane). Shown in Figures 3a-b is a lenslet array having a first side **128** and a second side **130** which is opposite to first side **128**. An array **132** of spherical lenses is arranged on the first side **128**, and an array **134** of cylindrical lenses is arranged on second side **130**. In the representative example illustrated in Figure 3a-b, the cylindrical lenses are oriented such that their curvature is along the horizontal direction. The focal plane of the spherical lenses in is denoted F_2 and the focal plane of the cylindrical lenses is denoted F_1. For clarity of presentation, only the longitudinal locations of the focal planes are illustrated in Figures 3a-b, but one of ordinary skill in the art would appreciate that the focal planes are transverse (parallel to the *x-y* plane) intersecting the longitudinal axis **108** at F_1 or F_2.

Since the cylindrical lenses are flat with respect to the *x* axis (Figure 3a), they do not contribute to light ray convergence or divergence in the vertical plane. Thus, the light rays are only refracted by the spherical lenses and the effective focal length of lenslet array in this plane is OF_2 where O is the longitudinal location of the effective center of the lenses. On the other hand, in the horizontal plane (Figure 3b) both the cylindrical and the spherical lenses contribute to light ray convergence or divergence, and the effective focal length in the horizontal length is the combination of OF_1 and OF_2.

The homogeneity of intensity distribution across the light beam can be improved by judicious selection of the lenslet array. In one embodiment, the array of cylindrical lenses and/or array of spherical lenses is corrugated so as to impart a substantially homogenous intensity distribution across the light beam. In another embodiment, the lenslet array is made, at least in part, of a diffractive material, *e.g.*, opal.

While the use of lenslet arrays is favored from the standpoints of design simplicity, overall size of apparatus **100** and ability to transmits a plurality of colors, other optical element are not excluded from the scope of the present invention. Thus,

linear focusing element **106** can also comprise one or more of the following optical elements: a condenser lens system, a Fresnel zone plate and a holographic lens.

The ability of apparatus **100** to provide different linear foci at different distances allows incorporating apparatus **100** in many virtual image display systems. In particular it is useful to incorporate apparatus **100** in systems which provide different linear expansion ratios in different transverse dimensions. For example, apparatus **100** can be incorporated in a virtual image display system having an optical relay device which expands a light beam in the horizontal dimension but maintains the linear size of the light beam in the vertical dimension.

Reference is now made to Figure 4 which is a schematic cross-sectional illustration in the horizontal plane of a system **200** for providing an image to a user, according to various exemplary embodiments of the present invention. System **200** can be designed either as a binocular system or as a monocular system for viewing a virtual image. For binocular view, system **200** allows light rays propagations such that when the user places one eye within one two-dimensional eye-box region **20** in space and another eye within another two-dimensional eye-box region **22** in space, the virtual image is perceived. For monocular view, system **200** allows light rays propagations such that the virtual image is perceived when the user places his or her eye within a single region **20**.

System **200** preferably comprises image generating apparatus **100** for providing light beam **104**. According to the presently preferred embodiment of the invention apparatus **100** comprises optical projection element **44** interposed in the optical path of the light beam and an optical relay device **10**. In the present embodiment, light beam **104** is modulated to constitute and image therein as described hereinabove. According to the presently preferred embodiment of the invention, element **44** is positioned at longitudinal location Z_1 along axis **108** and eye-box regions **20**, **22** are defined at longitudinal location Z_2.

Optical projection element **44** serves as a collimator which collimates light beam **104** and projects it onto an optical aperture **204** of relay device **10**.

Any projection element known in the art may be used. For example a converging lens (spherical or non spherical), an arrangement of lenses, a diffractive optical element and the like. The purpose of the collimating procedure is for improving the imaging ability. In case of a converging lens, a light ray going through

a typical converging lens that is normal to the lens and passes through its center, defines the optical axis. The bundle of rays passing through the lens cluster about this axis and may be well imaged by the lens, for example, if the source of the light is located as the focal plane of the lens, the image constituted by the light is projected to infinity.

Other collimating means, *e.g.*, a diffractive optical element, may also provide imaging functionality. The advantage of a converging lens is due to its minimal color aberrations, whereas the advantage of a diffractive optical element is due to its compactness.

Device **10** serves for relaying the collimated beam in a manner such that the light beam is expanded in the horizontal dimension and relayed to occupy eye-box regions **20** and/or **22**. Relay device **10** can be any relay device known in the art. For example, relay device **10** can operate according to the principles described in U.S. Patent No. 6,757,105, U.S. Patent Application No. 10/896,865 and U.S. Patent Application No. 11/017,920, all assigned to the same assignee as the present Application.

In operation, apparatus **100** forms one linear focus of the image on element **44** and another linear focus of image at eye-box region(s) **20, 22**.

When relay device **10** expands the light beam in the horizontal dimension but maintains the linear size of the light beam in the vertical dimension, the linear focus on element **44** is preferably with respect to the horizontal dimension, and the linear focus at the eye-box region(s), is preferably with respect to the vertical dimension. This is because in the horizontal dimension the expansion of the light beam is being provided by relay device **10** and there is no need to focus the image at the eye-box region(s). Complementarily, the linear focus at the eye-box region(s), is preferably with respect to the vertical dimension, so as to ensure expansion of the light beam also in the vertical dimension.

Thus, system **200** provides light expansion in both transverse direction, hence facilitates enlarged eye-box regions. Preferably, apparatus **100** is designed such that most, and more preferably the entire light beam arrives at the eye-box region(s), with minimal light being directed outside the eye-box. Thus, the present embodiments significantly reduce optical losses.

Reference is now made conjointly to Figures 5a-b and 6a-b which illustrate by way of an example the operation principles of system **200**. Figures 5a-b illustrate ray tracing within system **200** and Figures 6a-b are fragmentary schematic illustration of cross-sectional views of system **200**.

The ray tracing illustrations (Figures 5a-b) include the well-known and used symbols of geometric optics in which an object or image thereof is illustrated as an arrow and a converging or condensing lens is illustrated as a double sided arrow. The object in the ray tracing illustration represents the light source of the system, and the lenses represent the linear focusing element and the projection element of the system.

In the vertical plane (Figure 5a) an object which symbolizes light source **102** is located next to a condensing lens which symbolize linear focusing element **106**, within the focal length of the lens. The lens is a spherical lens with a focal length of the order of several millimeters, *e.g.*, about 4 mm. The focal point of the spherical lens if shown at F_2. The condensing lens **106** is positioned farther than the focal length of another converging lens which symbolize projection element **44**. As a representative example, the focal length of the projection element **44** can be about 25 mm. The focal point of this lens is shown at F_3. As shown in Figure 5a, an intermediate virtual image of the object is formed by the condensing lens **106** upstream the optical axis (behind the object) and a real image of the intermediate image is formed by the projection element **44** downstream the optical axis at location Z_1. Thus, the object (the light source) is imaged as a real image onto the eye-box region of system **200**.

The fragmentary schematic illustration (Figure 6a) exemplifies a realization of the optical principles in the vertical plane as follows. An LCD display panel is illuminated by an array of LEDs. In the side view illustration of Figure 6a the LED array is illustrated as a vertical stack of LEDs. Each LED in the vertical stack thus represents a row of LEDs in a two-dimensional LED array. As a representative example, the vertical dimension H of the LCD panel is 7 mm, and the horizontal dimension W (not shown, see Figure 6b) is 9 mm.

The LCD is located behind a lenslet array such that each row of LEDs (three shown in Figure 6a) is behind a row of lenslets of the lenslet array. Thus, the number of LEDs in the LED array is preferably the same as the number of lenslets in the lenslet array. The lenslet array includes spherical lenslets with a focal length of 4 mm and cylindrical lenslets with a focal length of 5.45 mm. However, in the side view

illustration of Figure 6a the cylindrical lenslets are not shown because, as stated, they do not contribute to light convergence or divergence in the vertical plane.

As shown, the lenslet array spans the entire vertical dimension of the LCD. The LEDs are located such that each LED is imaged by the spherical lenses and the projection lens as described above onto the eye-box region. As a representative example, the size of the eye-box region along the vertical dimension is about 8 mm. This can be achieved by ensuring that the distance between the centers of two adjacent LEDs is smaller than the distance between the axes of symmetry of two adjacent lenslets.

In the horizontal plane (Figure 5b), the projection element **44** is not shown for the clarity of presentation, however it is positioned at location Z_1, as shown in Figure 5a. The linear focusing element **106** is symbolized as two adjacent converging lenses, a spherical lens which also operates in the vertical plane, and a cylindrical lens which is oriented to operate in the horizontal plane but not in the vertical plane. The focal length of the cylindrical lens is also of order of several millimeters but longer than the focal length of the spherical lens. As a representative example, the focal length of the cylindrical lens is about 5.45 mm. The effective focal length of the two adjacent lens is shorter than the distance between the object and the lenses, and a real image is formed at location Z_1. More specifically, an intermediate virtual image of the object **102** is formed by the cylindrical lens behind the object between the focal points F_1 and F_2, and a real image of the intermediate image is formed by the spherical lens downstream the optical axis at location Z_1.

The fragmentary schematic illustration (Figure 6b) exemplifies a realization of the optical principles in the vertical plane as follows. The two-dimensional LED array is illustrated as horizontal stack of LEDs, each representing a column of LEDs in the array. Figure 6b illustrates four LEDs, representing four columns in the array. Thus, in the present example, the LED array includes four columns and three rows. As described above the LEDs illuminate the LCD panel.

The four LEDs are positioned behind the lenslet array. The lenslet array includes four spherical lenslets with a focal length of 4 mm and four cylindrical lenslets with a focal length of 5.45 mm. Each illustrated lenslet represents a column in a two-dimensional lenslet array. The lenslet array can be equal in width or wider than the width W of the LCD panel.

The effective width of the projection lens **44** is preferably the same as the aperture **204** of the relay device (not shown, see Figure 4). With such configuration, each LED can be imaged onto the projection lens. In the representative example illustrated in Figures 6a-b, the projection lens has a focal length of about 25 mm and an effective width of about 10 mm.

The principles and operations of optical relay device **10**, in accordance with preferred embodiments of the present invention will be now described. For the purpose of providing a self contained document, the description of device **10** is preceded by a brief description of various optical phenomena.

When a ray of light moving within a light-transmissive substrate and striking one of its internal surfaces at an angle ϕ_1 as measured from a normal to the surface, it can be either reflected from the surface or refracted out of the surface into the open air in contact with the substrate. The condition according to which the light is reflected or refracted is determined by Snell's law, which is mathematically realized through the following equation:

$$n_A \sin\phi_2 = n_S \sin\phi_1, \qquad \text{(EQ. 1)}$$

where n_S is the index of refraction of the light-transmissive substrate, n_A is the index of refraction of the medium outside the light transmissive substrate ($n_S > n_A$), and ϕ_2 is the angle in which the ray is refracted out, in case of refraction. Similarly to ϕ_1, ϕ_2 is measured from a normal to the surface. A typical medium outside the light transmissive substrate is air having an index of refraction of about unity.

As used herein, the term "about" refers to ±10 %.

As a general rule, the index of refraction of any substrate depends on the specific wavelength λ of the light which strikes its surface. Given the impact angle, ϕ_1, and the refraction indices, n_S and n_A, Equation 1 has a solution for ϕ_2 only for ϕ_1 which is smaller than arcsine of n_A/n_S often called the critical angle and denoted α_c. Hence, for sufficiently large ϕ_1 (above the critical angle), no refraction angle ϕ_2 satisfies Equation 1 and light energy is trapped within the light-transmissive substrate. In other words, the light is reflected from the internal surface as if it had stroked a mirror. Under these conditions, total internal reflection is said to take place. Since different wavelengths of light (*i.e.*, light of different colors) correspond to different indices of refraction, the condition for total internal reflection depends not only on the

angle at which the light strikes the substrate, but also on the wavelength of the light. In other words, an angle which satisfies the total internal reflection condition for one wavelength may not satisfy this condition for a different wavelength.

When a sufficiently small object or sufficiently small opening in an object is placed in the optical path of light, the light experiences a phenomenon called diffraction in which light rays change direction as they pass around the edge of the object or at the opening thereof. The amount of direction change depends on the ratio between the wavelength of the light and the size of the object/opening. In planar optics there is a variety of optical elements which are designed to provide an appropriate condition for diffraction. Such optical elements are typically manufactured as diffraction gratings which are located on a surface of a light-transmissive substrate. Diffraction gratings can operate in transmission mode, in which case the light experiences diffraction by passing through the gratings, or in reflective mode in which case the light experiences diffraction while being reflected off the gratings

Figure 7 schematically illustrates diffraction of light by a linear diffraction grating operating in transmission mode. One of ordinary skills in the art, provided with the details described herein would know how to adjust the description for the case of reflection mode.

A wavefront **1** of the light propagates along a vector $\underline{i}$ and impinges upon a grating **2** engaging the *x-y* plane. The normal to the grating is therefore along the z direction and the angle of incidence of the light ϕ_i is conveniently measured between the vector $\underline{i}$ and the z axis. In the description below, ϕ_i is decomposed into two angles, ϕ_{ix} and ϕ_{iy}, where ϕ_{ix} is the incidence angle in the *z-x* plane, and ϕ_{iy} is the incidence angle in the *z-y* plane. For clarity of presentation, only ϕ_{iy} is illustrated in Figure 7.

The grating has a periodic linear structure along a vector g, forming an angle θ_R with the y axis. The period of the grating (also known as the grating pitch) is denoted by D. The grating is formed on a light transmissive substrate having an index of refraction denoted by n_S.

Following diffraction by grating **2**, wavefront **1** changes its direction of propagation. The principal diffraction direction which corresponds to the first order of diffraction is denoted by $\underline{d}$ and illustrated as a dashed line in Figure 7. Similarly to the angle of incidence, the angle of diffraction ϕ_d, is measured between the vector $\underline{d}$ and

the z axis, and is decomposed into two angles, ϕ_{dx} and ϕ_{dy}, where ϕ_{dx} is the diffraction angle in the z-x plane, and ϕ_{dy} is the diffraction angle in the z-y plane.

The relation between the grating vector g, the diffraction vector $\underline{d}$ and the incident vector $\underline{i}$ can therefore be expressed in terms of five angles (θ_R, ϕ_{ix}, ϕ_{iy}, ϕ_{dx} and ϕ_{dy}) and it generally depends on the wavelength λ of the light and the grating period D through the following pair of equations:

$$\sin(\phi_{ix}) - n_S \sin(\phi_{dx}) = (\lambda/D)\sin(\theta_R) \qquad \text{(EQ. 2)}$$

$$\sin(\phi_{iy}) + n_S \sin(\phi_{dy}) = (\lambda/D)\cos(\theta_R). \qquad \text{(EQ. 3)}$$

Without the loss of generality, the Cartesian coordinate system can be selected such that the vector $\underline{i}$ lies in the y-z plane, hence $\sin(\phi_{ix}) = 0$. In the special case in which the vector g lies along the y axis, $\theta_R = 0°$ or $180°$, and Equations 2-3 reduce to the following one-dimensional grating equation:

$$\sin\phi_{iy} + n_S \sin\phi_{dy} = \pm\lambda/d. \qquad \text{(EQ. 4)}$$

According the known conventions, the sign of ϕ_{ix}, ϕ_{iy}, ϕ_{dx} and ϕ_{dy} is positive, if the angles are measured clockwise from the normal to the grating, and negative otherwise. The dual sign on the RHS of the one-dimensional grating equation relates to two possible orders of diffraction, +1 and −1, corresponding to diffractions in opposite directions, say, "diffraction to the right" and "diffraction to the left," respectively.

A light ray, entering a substrate through a grating, impinge on the internal surface of the substrate opposite to the grating at an angle which depends on the two diffraction components $\sin(\phi_{dx})$ and $\sin(\phi_{dy})$ according to the following equation:

$$\phi_d = \sin^{-1}\{[\sin^2(\phi_{dx}) + \sin^2(\phi_{dy})]^{1/2}\} \qquad \text{(EQ. 5)}$$

When ϕ_d is larger than the critical angle α_c, the wavefront undergoes total internal reflection and begin to propagate within the substrate.

Reference is now made to Figures 8a-c which are schematic illustrations of cross sectional views of an optical relay device **10**, according to various exemplary embodiments of the present invention. Figures 8a, 8b and 8c illustrate cross sectional views of device **10** in the x-y plane, y-z plane and the x-z plane, respectively. According to a preferred embodiment of the present invention device **10** comprises a light-transmissive substrate **14**, an input optical element **13** and an output optical element **15**. The system of coordinates in Figures 8a-c is selected such that substrate

14 is orthogonal to the *z* axis, and optical elements **13** and **15** are laterally displaced along the *y* axis. As above, the *z* axis is referred to as the "longitudinal" axis, and the *x* and *y* axes are referred to as the "transverse" axes. Thus, substrate **14** engages the transverse plane spanned by the *x-y* axes.

Element **13** redirects the light into substrate **14** such that at least a few light rays experience total internal reflection and propagate within substrate **14**. Element **15** serves for redirecting at least a few of the propagating light rays out of substrate **14**. Each of elements **13** and **15** can be a refractive element, a reflective element or a diffractive element.

In embodiments in which a refractive element is employed, element **13** and/or element **15** can comprise a plurality of linearly stretched mini- or micro-prisms, and the redirection of light is generally by the refraction phenomenon described by Snell's law. Thus, for example, when both elements **13** and **15** are refractive elements, element **13** refracts the light into substrate **14** such that at least a few light rays experience total internal reflection and propagate within substrate **14**, and element **15** refracts at least a few of the propagating light rays out of substrate **14**. Refractive elements in the form of mini- or micro-prisms are known in the art and are found, *e.g.*, in U.S. Patent Nos. 5,969,869, 6,941,069 and 6,687,010, the contents of which are hereby incorporated by reference.

In embodiments in which a reflective element is employed, element **13** and/or element **15** can comprises a plurality of dielectric mirrors, and the redirection of light is generally by the reflection phenomenon, described by the basic law of reflection. Thus, for example, when both elements **13** and **15** are reflective elements, element **13** reflects the light into substrate **14** such that at least a few light rays experience total internal reflection and propagate within substrate **14**, and element **15** reflects at least a few of the propagating light rays out of substrate **14**. Reflective elements in the form of dielectric mirrors are known in the art and are found, *e.g.*, in U.S. Patent Nos. 6,330,388 and 6,766,082, the contents of which are hereby incorporated by reference.

Element **13** and/or element **15** can also combine reflection with refraction. For example, element **13** and/or element **15** can comprise a plurality of partially reflecting surfaces located in substrate **14**. In this embodiment, the partially reflecting surfaces are preferably parallel to each other. Optical elements of this type are known in the art

and found, *e.g.*, in U.S. Patent No. 6,829,095, the contents of which are hereby incorporated by reference.

In embodiments in which diffractive element is employed, element **13** and/or **15** can comprise a grating and the redirection of light is generally by the diffraction phenomenon. Thus, for example, when both elements **13** and **15** are diffractive elements, element **13** diffracts the light into substrate **14** such that at least a few light rays experience total internal reflection and propagate within substrate **14**, and element **15** diffracts at least a few of the propagating light rays out of substrate **14**.

The term "diffracting" as used herein, refers to a change in the propagation direction of a wavefront, in either a transmission mode or a reflection mode. In a transmission mode, "diffracting" refers to change in the propagation direction of a wavefront while passing through the diffractive element; in a reflection mode, "diffracting" refers to change in the propagation direction of a wavefront while reflecting off the diffractive element in an angle different from the basic reflection angle (which is identical to the angle of incidence). In the exemplified illustration of Figure 8b, elements **13** and **15** are transmissive elements, *i.e.*, they operates in transmission mode.

Input element **13** is preferably designed and constructed such that the angle of light rays redirected thereby is above the critical angle, and the light propagates in the substrate via total internal reflection. The propagated light, after a few reflections within substrate **14**, reaches output element **15** which redirects the light out of substrate **14**.

When apparatus **100** is adapted to be used with relay device **10**, the linear focusing element **106** is preferably designed and constructed taking into account the optical distance between region **20** and element **106** rather than the Euclidian longitudinal distance therebetween. This is because in addition to the free space propagation of the light rays (*e.g.*, from focusing element **106** to projection element **44** and from projection element **44** to input element **13**) they also experience a plurality of total internal reflection within substrate **14** and as a consequence the length of the optical path is longer that the Euclidian distance. For example, when a particular light ray experiences N events of total internal reflection the difference between the Euclidian distance and the optical distance is about $N \times t$ where t is the thickness of substrate **14**.

It is appreciated, however, that the number of total internal reflection events for different light rays may differ (see, *e.g.*, rays **17** and **18** in Figure 8b). Thus, for a given longitudinal location Z_2 of region **20**, there are several different optical distances traveled by the light rays. Formally, denoting the Euclidian longitudinal distance between element **106** and region **20** by ΔZ_E, the optical path therebetween varies from a minimal optical distance of about $\Delta Z_E + N_{\min} t$ to a maximal optical distance of about $\Delta Z_E + N_{\max} t$, where $N_{\min}$ and $N_{\max}$ are, respectively, the minimal and maximal total internal reflection events which may occur within substrate **14**. In the case in which the thickness t is equal 2mm, a typical Euclidian longitudinal distance between element **106** and region **20** is about 52 mm, and a minimal optical distance is about 64 mm and a typical maximal optical distance is about 88 mm.

In various exemplary embodiments of the invention element **106** is selected such that focus **122** is formed at a distance which equals the average between the minimal and maximal optical distances. The average can be an arithmetic or geometric average. As will be appreciated by one of ordinary skill in the art, this can be ensured, for example, by a judicious selection of F_2 for a given F_3. Once F_2 is determined, F_1 can be calculated based on the desired Euclidian longitudinal distance between element **106** and plane **144**, where the effective center of projection element **44** is located.

Element **13** and/or element **15** is optionally and preferably a linear diffraction grating, operating according to the principles described above. When both elements **13** and **15** are linear ratings, their periodic linear structures are preferably substantially parallel. Elements **13** and **15** can be formed on or attached to any of the surfaces **23** and **24** of substrate **14**. Substrate **14** can be made of any light transmissive material, preferably, but not obligatorily, a martial having a sufficiently low birefringence. Element **15** is laterally displaced from element **13**. A preferred lateral separation between the elements is from a few millimeters to a few centimeters.

Device **10** is preferably designed to transmit light striking substrate **14** at any striking angle within a predetermined range of angles, which predetermined range of angles is referred to of the field-of-view of the device.

The input optical element is designed to trap all light rays in the field-of-view within the substrate. A field-of-view can be expressed either inclusively, in which case its value corresponds to the difference between the minimal and maximal incident

angles, or explicitly in which case the field-of-view has a form of a mathematical range or set. Thus, for example, a field-of-view, Ω, spanning from a minimal incident angle, α, to a maximal incident angle, β, is expressed inclusively as $\Omega = \beta - \alpha$, and exclusively as $\Omega = [\alpha, \beta]$. The minimal and maximal incident angles are also referred to as rightmost and leftmost incident angles or counterclockwise and clockwise field-of-view angles, in any combination. The inclusive and exclusive representations of the field-of-view are used herein interchangeably.

The field-of-view of device **10** is illustrated in Figures 8b-f by two of its outermost light rays, generally shown at **17** and **18**.

Figure 8b and 8c illustrate the projections of rays **17** and **18** on two planes which are parallel to the normal axis of device **10**. Specifically, Figure 8b illustrates the projections of rays **17** and **18** on a plane containing the horizontal axis of device **10** (the *y-z* plane in the present coordinate system) and Figure 8c illustrates the projections of rays **17** and **18** on a plane containing the vertical axis of device **10** (the *x-z* plane in the present coordinate system).

Below, the term "horizontal field-of-view" will be used to describe the ranges angles within the field-of-view as projected on the *y-z* plane, and the term "vertical field-of-view" or "vertical field-of-view" will be used to describe the ranges angles within the field-of-view as projected on the *x-z* plane.

Thus, Figure 8b schematically illustrates the horizontal field-of-view and Figure 8c schematically illustrates the vertical field-of-view of device **10**. In the horizontal field-of-view illustrated in Figure 8b, the projection of ray **18** is the rightmost ray projection which forms with the normal axis an angle denoted θ_y^-, and the projection of ray **17** is the leftmost ray projection which forms with the normal axis an angle denoted θ_y^+. In the vertical field-of-view illustrated in Figure 8c, the projection of ray **18** is the rightmost ray projection which forms with the normal axis an angle denoted θ_x^-, and the projection of ray **17** is the leftmost ray projection which forms with the normal axis an angle denoted θ_x^+. When substrate **14** is held with the vertical axis directed upwards, the projection of ray **18** is viewed as the uppermost ray projection and the projection of ray **17** is viewed as the lowermost ray projection.

In exclusive representations, the horizontal field-of-view, denoted Ω_y, is $[\theta_y^-, \theta_y^+]$ and the vertical field-of-view, denoted Ω_x is $[\theta_x^-, \theta_x^+]$. In the exemplified

illustration of Figures 8b and 8c the projections θ_x^-, θ_y^- are measured anticlockwise from the normal axis (the *z* axis in Figures 8b and 8c), and the projections θ^+_x, θ^+_y are measured clockwise from the normal axis. Thus, according to the above convention, θ_x^-, θ_y^- have negative values and θ^+_x, θ^+_y have positive values, resulting in a horizontal field-of-view $\Omega_y = \theta_y^+ + |\theta_y^-|$, and a vertical field-of-view $\Omega_x = \theta_x^+ + |\theta_x^-|$, in inclusive representations.

Figure 8d schematically illustrates the field-of-view in a plane orthogonal to the normal axis of device **10** (parallel to the *x-y* plane, in the present coordinate system). Rays **17** and **18** are points on this plane. For the purpose of simplifying the presentation, the field-of-view is illustrated as a rectangle, and the straight light connecting the points is the diagonal of the rectangle. Rays **17** and **18** are referred to as the "lower-left" and "upper-right" light rays of the field-of-view, respectively.

It is appreciated that the field-of-view can also have a planar shape other than a rectangle, include, without limitation, a square, a circle and an ellipse. One of ordinary skills in the art, provided with the details described herein would know how to adjust the description for non-rectangle field-of-view.

In exclusive representation, the diagonal field-of-view of device **10** is given by $\Omega = [\theta^-, \theta^+]$, where θ^- the angle between ray **17** and a line intersecting ray **17** and being parallel to the normal axis, and θ^+ is the angle between ray **18** and a line intersecting ray **18** and being parallel to the normal axis. Figures 8e and 8f illustrate the diagonal field-of-view angles θ^- and θ^+ in planes containing ray **17** and ray **18**, respectively. The relation between $\theta^\pm$ and their projections $\theta_x^\pm$, $\theta_y^\pm$ are given by Equation 5 above with the substitutions $\phi_d \rightarrow \theta^\pm$, $\phi_{dx} \rightarrow \theta_x^\pm$ and $\phi_{dy} \rightarrow \theta_y^\pm$. Unless specifically stated otherwise, the term "field-of-view angle" refers to a diagonal angle, such as $\theta^\pm$.

The light rays arriving to device **10** can have one or more wavelength. When the light has a plurality of wavelengths, the shortest wavelength is denoted λ_B and the longest wavelength is denoted λ_R, and the range of wavelengths from λ_B to λ_R is referred to herein as the spectrum of the light.

Irrespectively of the number of different wavelengths of the light, when the light rays in the field-of-view impinge on element **13**, they are preferably redirected at an angle (defined relative to the normal) which is larger than the critical angle, such

that upon striking the other surface of substrate **14**, all the light rays of the field-of-view experiences total internal reflection and propagate within substrate **14**.

In the representative illustration of Figures 8b-c, element **13** diffracts leftmost ray **17** and rightmost ray **18** into substrate **14** at diffraction angles denoted θ_d^+ and θ_d^-, respectively. Shown in Figures 8b-c are $\theta_{yd}^{\pm}$ (Figure 8b) and $\theta_{xd}^{\pm}$ (Figure 8b), which are the projections of $\theta_d^{\pm}$ on the *y-z* plane and the *x-z* plane, respectively.

While propagating, the rays are reflected from the internal surfaces of substrate **14**. The Euclidian distance between two successive points on the internal surface of the substrate at which a particular light ray experiences total internal reflection is referred to as the "hop length" of the light ray and denoted by "*h*". The propagated light, after a few reflections within substrate **14**, generally along the horizontal axis of device **10**, reaches output optical element **15** which redirects the light out of substrate **14**. Device **10** thus transmits at least a portion of the optical energy carried by each light ray between rays **17** and **18**. When the light rays within the field-of-view originate from an object which emits or reflects light, a viewer can position one or two eyes in front of element **15** to see a virtual image of the object.

As shown in Figure 8b, for a single impingement of a light ray on output element **15**, only a portion of the light energy exits substrate **14**. The remnant of each ray is redirected through an angle, which causes it, again, to experience total internal reflection from the other side of substrate **14**. After a first reflection, the remnant may re-strike element **15**, and upon each such re-strike, an additional part of the light energy exits substrate **14**. Thus, a light ray propagating in the substrate via total internal reflection exits the substrate in a form of a series of parallel light rays where the distance between two adjacent light rays in the series is *h*. Such series of parallel light rays corresponds to a collimated light beam exiting element **15**. Since more than one light ray exit as a series of parallel light rays, a beam of light passing through device **10** is expanded in a manner that the cross sectional area of the outgoing beam is larger than cross sectional area of the incoming beam.

According to a preferred embodiment of the present invention output optical element **15** is characterized by planar dimensions selected such that at least a portion of one or more outermost light rays within the field-of-view is directed to a two-dimensional region **20** being at a predetermined distance Δz from light transmissive

substrate **14**. More preferably, the planar dimensions of element **15** are selected such that the outgoing light beam enters region **20**.

To ensure entering of the outermost light ray or the entire outgoing light beam into region **20**, the length L_O of element **15** is preferably selected to be larger then a predetermined length threshold, $L_{O,\,min}$, and the width W_O of element **15** is preferably selected to be larger then a predetermined width threshold, $W_{O,\,min}$. In various exemplary embodiments of the invention the length and width thresholds are given by the following expressions:

$$L_{O,\,min} = 2\,\Delta z\,\tan(\Omega_y/2)$$
$$W_{O,\,min} = 2\,\Delta z\,\tan(\Omega_x/2). \qquad \text{(EQ. 6)}$$

When device **10** is used for viewing a virtual image, the user may place his or her eye(s) within region **20** to view the virtual image. Thus, in this embodiment, region **20** is the "eye-box" of device **10**, and Δz is approximately the distance between the pupil(s) of the user to substrate **14**. The distance Δz is referred to herein as the characteristic eye-relief of device **10**. For transmitting an image to one eye, the length L_O and width W_O of element **15** are preferably about $L_{O,\,min} + O_p$, and about $W_{O,\,min} + O_p$, respectively, where O_p represents the diameter of the pupil and is typically about 3 millimeters. In various exemplary embodiments of the invention the eye-box is larger than the diameter of the pupil, so as to allow the user to relocate the eye within the eye-box while still viewing the entire virtual image. Thus, denoting the dimensions of region **20** by L_{EB} and W_{EB}, where L_{EB} is measured along the y axis and W_{EB} is measured along the x axis, the length and width of element **15** are preferably:

$$L_O = L_{O,\,min} + L_{EB}$$
$$W_O = W_{O,\,min} + W_{EB}, \qquad \text{(EQ. 7)}$$

where each of L_{EB} and W_{EB} is preferably larger than O_p, so as to allow the user to relocate the eye within region **20** while still viewing the entire field-of-view.

The dimensions of input optical element **13** are preferably selected to allow all light rays within the field-of-view to propagate in substrate **14** such as to impinge on the area of element **15**. In various exemplary embodiments of the invention the length L_I of input element **13** equals from about X to about $3X$ where X is preferably a unit hop-length characterizing the propagation of light rays within substrate **14**. Typically, X equals the hop-length of the light-ray with the minimal hop-length, which is one of the outermost light-rays in the field-of-view (ray **18** in the exemplified illustration of

Figure 8b). When the light has a plurality of wavelengths, X is typically the hop-length of one of the outermost light-rays which has the shortest wavelength of the spectrum.

According to a preferred embodiment of the present invention the width W_O of element **15** is smaller than the width W_I of element **13**. W_I is preferably calculated based on the relative arrangement of elements **13** and **15**. For example, in one embodiment, elements **13** and **15** are centrally aligned with respect to the vertical axis of device **10** (but laterally displaced along the horizontal axis and optionally displaced also along the normal axis). In the present coordinate system this central alignment correspond to equal x coordinate for a central width line **130** (connecting half width points of element **13**) and a central width line **150** (connecting half width points of element **15**). In this embodiment, the relation between W_I is preferably given by the following expression:

$$W_I = 2\,(L_O + \Delta y)\tan\gamma + W_O, \qquad \text{(EQ. 8)}$$

where Δy is the lateral separation between element **13** and element **15** along the horizontal axis of device **10** and γ is a predetermined angular parameter. Geometrically, γ is the angle formed between the horizontal axis and a straight line connecting the corner of element **13** which is closest to element **15** and the corner of element **15** which is farthest from element **13** (see, *e.g.*, line **12** in Figure 8a).

Preferably, γ relates to the propagation direction of one or more of the outermost light rays of the field-of-view within the substrate, as projected on a plane parallel to the substrate. In various exemplary embodiments of the invention γ equals the angle formed between the horizontal axis of the substrate and the propagation direction of an outermost light ray of the field-of-view, as projected on a plane parallel to the substrate.

Consider, for example, the "upper-right" light ray of the field-of-view impinging on element **13** at a field-of-view angle θ^- which is decomposed, according to the Cartesian coordinate system described above, into of angles θ_x^- (measured in the x-z plane) and θ_y^- (measured in the y-z plane). Using Equations 2 and 3 above, the corresponding components θ_{xd} and θ_{yd} of the diffraction angle θ_d can be calculated, *e.g.*, by selecting a value of 0° to θ_R. The propagation of the "upper-right" light ray in the substrate, can then be projected on a plane parallel to the substrate (the x-y plane in

the present coordinate system), thereby forming a vector in the x-y plane. According to a preferred embodiment of the present invention γ is set to the angle formed between the projected vector and the y axis, which can be written in the form: $\gamma = \tan^{-1}[\sin(\theta_{xd})/\sin(\theta_{yd})]$. A typical value for the absolute value of γ is, without limitation, from about 6° to about 15°.

Thus, a viewer placing his or her eye in region **20** of dimensions $L_{EB} \times W_{EB}$, receives at least a portion of any light ray within the field-of-view, provided the distance between the eye and element **15** equals Δz or is smaller than Δz.

The preferred value for Δz is, without limitation, from about 15 millimeters to about 35 millimeters, the preferred value for Δy is, without limitation, from a few millimeters to a few centimeters, the preferred value for L_{EB} is, without limitation, from about 5 millimeters to about 13 millimeters, and the preferred value for W_{EB} is, without limitation, is from about 4 millimeters to about 9 millimeters. For a given field-of-view, selection of large Δz results in smaller eye-box dimensions L_{EB} and W_{EB}, as known in the art. Conversely, small Δz allows for larger eye-box dimensions L_{EB} and W_{EB}.

$L_{O,\,min}$ and $W_{O,\,min}$ are preferably calculated using Equation 6, and together with the selected dimensions of region **20** (L_{EB} and W_{EB}), the dimensions of element **15** (L_O and W_O) can be calculated using Equation 7.

Once L_O and W_O are calculated, the vertical dimension W_I of input element **13** is preferably calculated by selecting values for Δy and γ and using Equation 8. The horizontal dimension L_I is generally selected from about 3 millimeters and about 15 millimeters.

In a preferred embodiment in which surfaces **23** and **24** of substrate **14** are substantially parallel, elements **13** and **15** can be designed, for a given spectrum, solely based on the value of θ^- and the value of the shortest wavelength λ_B. For example, when the optical elements are linear gratings, the period, D, of the gratings can be selected based on θ^- and λ_B, irrespectively of the optical properties of substrate **14** or any wavelength longer than λ_B.

According to a preferred embodiment of the present invention D is selected such that the ratio λ_B/D is from about 1 to about 2. A preferred expression for D is given by the following equation:

$$D = \lambda_B/[n_A(1 - \sin\theta^-)]. \qquad \text{(EQ. 9)}$$

It is appreciated that D, as given by Equation 9, is a maximal grating period. Hence, in order to accomplish total internal reflection D can also be smaller than $\lambda_B/[n_A(1-\sin\theta^-)]$.

Substrate **14** is preferably selected such as to allow light having any wavelength within the spectrum and any striking angle within the field-of-view to propagate in substrate **14** via total internal reflection.

According to a preferred embodiment of the present invention the refraction index of substrate **14** is larger than $\lambda_R/D + n_A\sin(\theta^+)$. More preferably, the refraction index, n_S, of substrate **14** satisfies the following equation:

$$n_S \geq [\lambda_R/D + n_A\sin(\theta^+)]/\sin(\alpha_D^{MAX}). \qquad \text{(EQ. 10)}$$

where α_D^{MAX} is the largest diffraction angle, *e.g.*, the diffraction angle of the light ray **17**. There are no theoretical limitations on α_D^{MAX}, except from a requirement that it is positive and smaller than 90 degrees. α_D^{MAX} can therefore have any positive value smaller than 90°. Various considerations for the value α_D^{MAX} are found in U.S. Patent No. 6,757,105, the contents of which are hereby incorporated by reference.

The thickness, t, of substrate **14** is preferably from about 0.1 mm to about 5 mm, more preferably from about 1 mm to about 3 mm, even more preferably from about 1 to about 2.5 mm. For multicolor use, t is preferably selected to allow simultaneous propagation of plurality of wavelengths, *e.g.*, $t > 10\,\lambda_R$. The width/length of substrate **14** is preferably from about 10 mm to about 100 mm. A typical width/length of the diffractive optical elements depends on the application for which device **10** is used. For example, device **10** can be employed in a near eye display, such as the display described in U.S. Patent No. 5,966,223, in which case the typical width/length of the diffractive optical elements is from about 5 mm to about 20 mm. The contents of U.S. Patent Application No. 60/716,533, which provides details as to the design of the diffractive optical elements and the selection of their dimensions, are hereby incorporated by reference.

For different viewing applications, such as the application described in U.S. Patent No. 6,833,955, the contents of which are hereby incorporated by reference, the length of substrate **14** can be 1000 mm or more, and the length of diffractive optical element **15** can have a similar size. When the length of the substrate is longer than

100 mm, then t is preferably larger than 5 millimeters. This embodiment is advantageous because it reduces the number of hops and maintains the substrate within reasonable structural/mechanical conditions.

Device **10** is capable of transmitting light having a spectrum spanning over at least 100 nm. More specifically, the shortest wavelength, λ_B, generally corresponds to a blue light having a typical wavelength of between about 400 to about 500 nm and the longest wavelength, λ_R, generally corresponds to a red light having a typical wavelength of between about 600 to about 700 nm.

As can be understood from the geometrical configuration illustrated in Figures 8b-c, the angles at which light rays **18** and **17** are redirected can differ. As the angles of redirection depend on the incident angles (see, *e.g.*, Equations 2-5 for the case of diffraction), the allowed clockwise (θ^+) and anticlockwise (θ^-) field-of-view angles, are also different. Thus, device **10** supports transmission of asymmetric field-of-view in which, say, the clockwise field-of-view angle is greater than the anticlockwise field-of-view angle. The difference between the absolute values of the clockwise and anticlockwise field-of-view angles can reach more than 70 % of the total field-of-view.

This asymmetry can be exploited in accordance with various exemplary embodiments of the present invention, to enlarge the field-of-view of optical device **10**. According to a preferred embodiment of the present invention, a light-transmissive substrate can be formed with at least one input optical element and two or more output optical elements. The input optical element(s) serve for redirecting the light into the light-transmissive substrate in a manner such that different portions of the light, corresponding to different partial field-of-views, propagate within the substrate in different directions to thereby reach the output optical elements. The output optical elements redirect the different portions of the light out of the light-transmissive substrate.

In accordance with the present embodiments, the planar dimensions of the output and/or input optical elements can be selected to facilitate the transmission of the partial field-of-views. The output optical elements can also be designed and constructed such that the redirection of the different portions of the light is in complementary manner.

The terms "complementarily" or "complementary," as used herein in conjunction with a particular observable or quantity (*e.g.*, field-of-view, image,

spectrum), refer to a combination of two or more overlapping or non-overlapping parts of the observable or quantity, which combination provides the information required for substantially reconstructing the original observable or quantity.

Any number of input/output optical elements can be used. Additionally, the number of input optical elements and the number of output optical elements may be different, as two or more output optical elements may share the same input optical element by optically communicating therewith. The input and output optical elements can be formed on a single substrate or a plurality of substrates, as desired. For example, in one embodiment, the input and output optical elements comprise linear diffraction gratings of identical periods, formed on a single substrate, preferably in a parallel orientation.

If several input/output optical elements are formed on the same substrate, as in the above embodiment, they can engage any side of the substrate, in any combination.

One ordinarily skilled in the art would appreciate that this corresponds to any combination of transmissive and reflective optical elements. Thus, for example, suppose that there is one input optical element, formed on surface **23** of substrate **14** and two output optical elements formed on surface **24**. Suppose further that the light impinges on surface **23** and it is desired to diffract the light out of surface **24**. In this case, the input optical element and the two output optical elements are all transmissive, so as to ensure that entrance of the light through the input optical element, and the exit of the light through the output optical elements. Alternatively, if the input and output optical elements are all formed on surface **23**, then the input optical element remain transmissive, so as to ensure the entrance of the light therethrough, while the output optical elements are reflective, so as to reflect the propagating light at an angle which is sufficiently small to couple the light out. In such configuration, light can enter the substrate through the side opposite the input optical element, be diffracted in reflection mode by the input optical element, propagate within the light transmissive substrate in total internal diffraction and be diffracted out by the output optical elements operating in a transmission mode.

Reference is now made to Figures 9a-b which are schematic illustrations of a perspective view (Figure 9a) and a side view (Figure 9b) of device **10**, in a preferred embodiment in which one input optical element **13** and two output optical elements **15**

and **19** are employed. In this embodiment, device **10** can be used as a binocular device for transmitting light to a first eye **25** and a second eye **30** of a user.

In Figure 9b, first **15** and second **19** output optical elements are formed, together with input optical element **13**, on surface **23** of substrate **14**. However, as stated, this need not necessarily be the case, since, for some applications, it may be desired to form the input/output optical elements on any of the surfaces of substrate **14**, in an appropriate transmissive/reflective combination. Wavefront propagation within substrate **14**, according to various exemplary embodiments of the present invention, is further detailed hereinunder with reference to Figures 10a-b.

Element **13** preferably redirects the incoming light into substrate **14** in a manner such that different portions of the light, corresponding to different partial fields-of-view, propagate in different directions within substrate **14**. In the configuration exemplified in Figures 9a-b, element **13** redirects light rays within one asymmetric partial field-of-view, designated by reference numeral **26**, leftwards to impinge on element **15**, and another asymmetric partial field-of-view, designated by reference numeral **32**, to impinge on element **19**. Elements **15** and **19** complementarily redirect the respective portions of the light, or portions thereof, out of substrate **14**, to provide first eye **25** with partial field-of-view **26** and second eye **30** with partial field-of-view **32**.

Partial field-of-views **26** and **32** form together the field-of-view **27** of device **10**. Similarly to the embodiments in which one output optical element is employed (see, *e.g.*, Figures 8a-c) elements **15** and **19** are characterized by planar dimensions selected such that at least a portion of one or more outermost light rays within partial field-of-view **26** is directed to two-dimensional region **20**, and at least a portion of one or more outermost light rays within partial field-of-view **32** is directed to another two-dimensional region **22**. This can be achieved by selecting the lengths and widths of elements **15** and **19** to be larger then predetermined length and width thresholds, as described above (see Equations 6-7).

Preferably, but not obligatorily, the planar dimensions of region **20** equal the planar dimensions of region **22**. Thus, the planar dimensions of each of regions **20** and **22** as well as the distance Δz are preferably within the aforementioned ranges.

In various exemplary embodiments of the invention the lateral separation between the horizontal centers of regions **20** and **22** is at least 40 millimeters.

Preferably, the lateral separation between the horizontal centers of regions **20** and **22** is less than 80 millimeters. According to a preferred embodiment of the present invention the planar dimensions of elements **15** and **19** are selected such that the portions of outermost light rays are respectively directed to regions **20** and **22**, for any lateral separation between the regions which is larger than 40 millimeters and smaller than 80 millimeters.

When device **10** is used for transmitting light to the eyes of the user, the planar dimensions of elements **15** and **19** are preferably selected such that eyes **25** and **30** are respectively provided with partial field-of-views **26** and **32** for any interpupillary distance IPD satisfying $IPD_{min} \leq IPD \leq IPD_{max}$.

This is preferably ensured by selecting the lengths L_{EB} of regions **20** and **22** according to the following weak inequality:

$$L_{EB} \geq (IPD_{max} - IPD_{min})/2. \qquad \text{(EQ. 11)}$$

Once L_{EB} is selected to satisfy Equation 11, the lengths and widths of output elements **15** and **19** can be set according to Equations 7 substantially as described hereinabove. According to a preferred embodiment of the present invention the horizontal center of each of elements **15** and **19** is located at a distance of $(IPD_{max} + IPD_{min})/4$ from the horizontal center element **13**.

The width W_I of element **13** is preferably larger than width of each of elements **15** and **19**. The calculation of W_I is preferably, but not obligatorily, performed using a procedure similar to the procedure described above, see Equation 8. When it is desired to manufacture a symmetric optical relay, the same planar dimensions $L_O \times W_O$ are used for both output elements **15** and **19**, and the same lateral separation Δy is used between elements **13** and **15** and between elements **13** and **19**. In this case, the width W_I of the input element can be set according to Equation 8 using the angular parameter γ as described above. Equation 8 can also be used in for configuration in which the lateral separation between elements **13** and **15** differs from the lateral separation between elements **13** and **19**. In this case the value of Δy which is used in the calculation is preferably set to the larger of the two lateral separations.

When device **10** is used for transmitting an image **34**, field-of-view **27** preferably includes substantially all light rays originated from image **34**. Partial fields-of-view **26** and **32** can therefore correspond to different parts of image **34**, which different parts are designated in Figure 9b by numerals **36** and **38**. Thus, as

shown in Figure 9b, there is at least one light ray **42** which enters device **10** via element **13** and exits device **10** via element **19** but not via element **15**. Similarly, there is at least one light ray **43** which enters device **10** via element **13** and exits device **10** via element **15** but not via element **19**.

Generally, the partial field-of-views, hence also the parts of the image arriving to each eye depend on the wavelength of the light. Therefore, it is not intended to limit the scope of the present embodiments to a configuration in which part **36** is viewed by eye **25** and part **38** viewed by eye **30**. In other words, for different wavelengths, part **36** is viewed by eye **30** and part **38** viewed by eye **25**. For example, when the image is constituted by a light having three colors: red, green and blue, device **10** can be constructed such that eye **25** sees part **38** for the blue light and part **36** for the red light, while eye **30** sees part **36** for the blue light and part **38** for the red light. In such configuration, both eyes see an almost symmetric field-of-view for the green light. Thus, for every color, the two partial fields-of-view compliment each other.

The human visual system is known to possess a physiological mechanism capable of inferring a complete image based on several parts thereof, provided sufficient information reaches the retinas. This physiological mechanism operates on monochromatic as well as chromatic information received from the rod cells and cone cells of the retinas. Thus, in a cumulative nature, the two asymmetric field-of-views, reaching each individual eye, form a combined field-of-view perceived by the user, which combined field-of-view is wider than each individual asymmetric field-of-view.

According to a preferred embodiment of the present invention, there is a predetermined overlap between first **26** and second **32** partial fields-of-view, which overlap allows the user's visual system to combine parts **36** and **38** of image **34**, thereby to perceive the image, as if it has been fully observed by each individual eye.

For example, the optical elements can be constructed such that the exclusive representations of partial fields-of-view **26** and **32** are, respectively, $[-\alpha, \beta]$ and $[-\beta, \alpha]$, resulting in a symmetric combined field-of-view **27** of $[-\beta, \beta]$. It will be appreciated that when $\beta >> \alpha > 0$, the combined field-of-view is considerably wider than each of the asymmetric field-of-views. Device **10** is capable of transmitting a field-of-view of at least 20 degrees, more preferably at least 30 degrees most preferably at least 40 degrees, in inclusive representation.

When the image is a multicolor image having a spectrum of wavelengths, different sub-spectra correspond to different, wavelength-dependent, asymmetric partial field-of-views, which, in different combinations, form different wavelength-dependent combined fields-of-view. For example, a red light can correspond to a first red asymmetric partial field-of-view, and a second red asymmetric partial field-of-view, which combine to a red combined field-of-view. Similarly, a blue light can correspond to a first blue asymmetric partial field-of-view, and a second blue asymmetric partial field-of-view, which combine to a blue combined field-of-view, and so on. Thus, a multicolor configuration is characterized by a plurality of wavelength-dependent combined field-of-views. According to a preferred embodiment of the present invention the optical elements are designed and constructed so as to maximize the overlap between two or more of the wavelength-dependent combined field-of-views.

In terms of spectral coverage, the design of device **10** is preferably as follows: element **15** provides eye **25** with, say, a first sub-spectrum which originates from part **36** of image **34**, and a second sub-spectrum which originates from part **38** of image **34**. Element **19** preferably provides the complementary information, so as to allow the aforementioned physiological mechanism to infer the complete spectrum of the image. Thus, element **19** preferably provides eye **30** with the first sub-spectrum originating from part **38**, and the second sub-spectrum originating from part **36**.

Ideally, a multicolor image is a spectrum as a function of wavelength, measured at a plurality of image elements. This ideal input, however, is rarely attainable in practical systems. Therefore, the present embodiment also addresses other forms of imagery information. A large percentage of the visible spectrum (color gamut) can be represented by mixing red, green, and blue colored light in various proportions, while different intensities provide different saturation levels. Sometimes, other colors are used in addition to red, green and blue, in order to increase the color gamut. In other cases, different combinations of colored light are used in order to represent certain partial spectral ranges within the human visible spectrum.

In a different form of color imagery, a wide-spectrum light source is used, with the imagery information provided by the use of color filters. The most common such system is using white light source with cyan, magenta and yellow filters, including a complimentary black filter. The use of these filters could provide representation of

spectral range or color gamut similar to the one that uses red, green and blue light sources, while saturation levels are attained through the use of different optical absorptive thickness for these filters, providing the well known "grey levels."

Thus, the multicolored image can be displayed by three or more channels, such as, but not limited to, Red-Green-Blue (RGB) or Cyan-Magenta-Yellow-Black (CMYK) channels. RGB channels are typically used for active display systems (*e.g.*, CRT or OLED) or light shutter systems (*e.g.*, Digital Light Processing™ (DLP™) or LCD illuminated with RGB light sources such as LEDs). CMYK images are typically used for passive display systems (*e.g.*, print). Other forms are also contemplated within the scope of the present invention.

When the multicolor image is formed from a discrete number of colors (*e.g.*, an RGB display), the sub-spectra can be discrete values of wavelength. For example, a multicolor image can be provided by an OLED array having red, green and blue organic diodes (or white diodes used with red, green and blue filters) which are viewed by the eye as continues spectrum of colors due to many different combinations of relative proportions of intensities between the wavelengths of light emitted thereby. For such images, the first and the second sub-spectra can correspond to the wavelengths emitted by two of the blue, green and red diodes of the OLED array, for example the blue and red. Device **10** can be constructed such that, say, eye **30** is provided with blue light from part **36** and red light from part **38** whereas eye **25** is provided with red light from part **36** and blue light from part **38**, such that the entire spectral range of the image is transmitted into the two eyes and the physiological mechanism reconstructs the image.

The light arriving at the input optical element of device **10** is preferably collimated, by a projection element or collimator **44** as described above. Collimator **44** can be, for example, a converging lens (spherical or non spherical), an arrangement of lenses and the like. Collimator **44** can also be a diffractive optical element, which may be spaced apart, carried by or formed in substrate **14**. A diffractive collimator may be positioned either on the entry surface of substrate **14**, as a transmissive diffractive element or on the opposite surface as a reflective diffractive element.

Following is a description of the principles and operations of optical device **10**, in the preferred embodiments in which device **10** comprises one input optical element and two output optical elements.

Reference is now made to Figures 10a-b which are schematic illustrations of wavefront propagation within substrate **14**, according to preferred embodiments in which diffractive elements are employed. Shown in Figures 10a-b are four principal light rays, **51**, **52**, **53** and **54**, respectively emitted from four points, **A**, **B**, **C** and **D**, of image **34**. The illustrations in Figures 10a-b lie in the *y-z* plane. The projections of the incident angles of rays **51**, **52**, **53** and **54** onto the *y-z* plane relative to the normal axis are denoted α_I^{--}, α_I^{-+}, α_I^{+-} and α_I^{++}, respectively. As will be appreciated by one of ordinary skill in the art, the first superscript index refer to the position of the respective ray relative to the center of the field-of-view, and the second superscript index refer to the position of the respective ray relative to the normal from which the angle is measured, according to the aforementioned sign convention.

It is to be understood that this sign convention cannot be considered as limiting, and that one ordinarily skilled in the art can easily practice the present invention employing an alternative convention.

Similar notations will be used below for diffraction angles of the rays, with the subscript *D* replacing the subscript *I*. Denoting the superscript indices by a pair *i*, *j*, an incident angle is denoted generally as α_I^{ij}, and a diffraction angle is denoted generally as α_D^{ij}, where $i\,j$ = "− −", "− +", "+ −" or "− −". The relation between each incident angle, α_I^{ij}, and its respective diffraction angle, α_D^{ij}, is given by Equation 4, above, with the replacements $\phi_{iy} \rightarrow \alpha_I^{ij}$, and $\phi_{dy} \rightarrow \alpha_D^{ij}$.

Points **A** and **D** represent the left end and the right end of image **34**, and points **B** and **C** are located between points **A** and **D**. Thus, rays **51** and **53** are the leftmost and the rightmost light rays of a first asymmetric field-of-view, corresponding to a part **A-C** of image **34**, and rays **52** and **54** are the leftmost and the rightmost light rays of a second asymmetric field-of-view corresponding to a part **B-D** of image **34**. In angular notation, the first and second asymmetric field-of-views are, respectively, $[\alpha_I^{--}, \alpha_I^{+-}]$ and $[\alpha_I^{-+}, \alpha_I^{++}]$ (exclusive representations). Note that an overlap field-of-view between the two asymmetric field-of-views is defined between rays **52** and **53**, which overlap equals $[\alpha_I^{-+}, \alpha_I^{+-}]$ and corresponds to an overlap **B-C** between parts **A-C** and **B-D** of image **34**.

In the configuration shown in Figures 10a-b, lens **45** magnifies image **34** and collimates the wavefronts emanating therefrom. For example, light rays **51-54** pass

through a center of lens **45**, impinge on substrate **14** at angles α_I^{ij} and diffracted by input optical element **13** into substrate **14** at angles α_D^{ij}. For the purpose of a better understanding of the illustrations in Figures 10a-b, only two of the four diffraction angles (to each side) are shown in each figure, where Figure 10a shows the diffraction angles to the right of rays **51** and **53** (angles α_D^{+-} and α_D^{--}), and Figure 10b shows the diffraction angles to the right of rays **52** and **54** (angles α_D^{-+} and α_D^{++}).

Each diffracted light ray experiences a total internal reflection upon impinging on the inner surfaces of substrate **14** if $|\alpha_D^{ij}|$, the absolute value of the diffraction angle, is larger than the critical angle α_c. Light rays with $|\alpha_D^{ij}| < \alpha_c$ do not experience a total internal reflection hence escape from substrate **14**. Generally, because input optical element **13** diffracts the light both to the left and to the right, a light ray may, in principle, split into two secondary rays each propagating in an opposite direction within substrate **14**, provided the diffraction angle of each of the two secondary rays is larger than α_c. To ease the understanding of the illustrations in Figures 10a-b, secondary rays diffracting leftward and rightward are designated by a single and double prime, respectively.

Reference is now made to Figure 10a showing a particular and preferred embodiment in which $|\alpha_D^{-+}| = |\alpha_D^{+-}| = \alpha_c$. Shown in Figure 10a are rightward propagating rays **51''** and **53''**, and leftward propagating rays **52'** and **54'**. Hence, in this embodiment, element **13** split all light rays between ray **51** and ray **52** into two secondary rays, a left secondary ray, impinging on the inner surface of substrate **14** at an angle which is smaller than α_c, and a right secondary ray, impinging on the inner surface of substrate **14** at an angle which is larger than α_c. Thus, light rays between ray **51** and ray **52** can only propagate rightward within substrate **14**. Similarly, light rays between ray **53** and ray **54** can only propagate leftward. On the other hand, light rays between rays **52** and **53**, corresponding to the overlap between the asymmetric field-of-views, propagate in both directions, because element **13** split each such ray into two secondary rays, both impinging the inner surface of substrate **14** at an angle larger than the critical angle, α_c.

Thus, light rays of the asymmetrical field-of-view defined between rays **51** and **53** propagate within substrate **14** to thereby reach second output optical element **19** (not shown in Figure 10a), and light rays of the asymmetrical field-of-view defined

between rays **52** and **54** propagate within substrate **14** to thereby reach first output optical element **15** (not shown in Figure 10a).

In another embodiment, illustrated in Figure 10b, the light rays at the largest entry angle split into two secondary rays, both with a diffraction angle which is larger than α_c, hence do not escape from substrate **14**. However, whereas one secondary ray experience a few reflections within substrate **14**, and thus successfully reaches its respective output optical element (not shown), the diffraction angle of the other secondary ray is too large for the secondary ray to impinge the other side of substrate **14**, so as to properly propagate therein and reach its respective output optical element.

Specifically shown in Figure 10b are original rays **51**, **52**, **53** and **54** and secondary rays **51'**, **52''**, **53'** and **54''**. Ray **54** splits into two secondary rays, ray **54'** (not shown) and ray **54''** diffracting leftward and rightward, respectively. However, whereas rightward propagating ray **54''** diffracted at an angle α_D^{++} experiences a few reflection within substrate **14** (see Figure 10b), leftward propagating ray **54'** either diffracts at an angle which is too large to successfully reach element **15**, or evanesces.

Similarly, ray **52** splits into two secondary rays, **52'** (not shown) and **52''** diffracting leftward and rightward, respectively. For example, rightward propagating ray **52''** diffracts at an angle $\alpha_D^{-+} > \alpha_c$. Both secondary rays diffract at an angle which is larger than α_c, experience one or a few reflections within substrate **14** and reach output optical element **15** and **19** respectively (not shown). In the case that α_D^{-+} is the largest angle for which the diffracted light ray will successfully reach the optical output element **19**, all light rays emitted from part **A-B** of the image do not reach element **19** and all light rays emitted from part **B-D** successfully reach element **19**. Similarly, if angle α_D^{+-} is the largest angle (in absolute value) for which the diffracted light ray will successfully reach optical output element **15**, then all light rays emitted from part **C-D** of the image do not reach element **15** and all light rays emitted from part **A-C** successfully reach element **15**.

Thus, light rays of the asymmetrical field-of-view defined between rays **51** and **53** propagate within substrate **14** to thereby reach output optical element **15**, and light rays of the asymmetrical field-of-view defined between rays **52** and **54** propagate within substrate **14** to thereby reach output optical element **19**.

Any of the above embodiments can be successfully implemented by a judicious design of the monocular devices, and, more specifically the input/output optical elements and the substrate.

For example, as stated, the input and output optical elements can be linear diffraction gratings having identical periods and being in a parallel orientation. This embodiment is advantageous because it is angle-preserving. Specifically, the identical periods and parallelism of the linear gratings ensure that the relative orientation between light rays exiting the substrate is similar to their relative orientation before the impingement on the input optical element. Consequently, light rays emanating from a particular point of the overlap part **B-C** of image **34**, hence reaching both eyes, are parallel to each other. Thus, such light rays can be viewed by both eyes as arriving from the same angle in space. It will be appreciated that with such configuration viewing convergence is easily obtained without eye-strain or any other inconvenience to the viewer, unlike the prior art binocular devices in which relative positioning and/or relative alignment of the optical elements is necessary.

According to a preferred embodiment of the present invention the period, D, of the gratings and/or the refraction index, n_S, of the substrate can be selected so to provide the two asymmetrical field-of-views, while ensuring a predetermined overlap therebetween. This can be achieved in more than one way.

Hence, in one embodiment, a ratio between the wavelength, λ, of the light and the period D is larger than or equal a unity:

$$\lambda/D \geq 1. \quad \text{(EQ. 12)}$$

This embodiment can be used to provide an optical device operating according to the aforementioned principle in which there is no mixing between light rays of the non-overlapping parts of the field-of-view (see Figure 10a).

In another embodiment, the ratio λ/D is smaller than the refraction index, n_S, of the substrate. More specifically, D and n_S can be selected to comply with the following inequality:

$$D > \lambda/(n_S\, p), \quad \text{(EQ. 13)}$$

where p is a predetermined parameter which is smaller than 1.

The value of p is preferably selected so as to ensure operation of the device according to the principle in which some mixing is allowed between light rays of the non-overlapping parts of the field-of-view, as further detailed hereinabove (see Figure

10b). This can be done for example, by setting $p = \sin(\alpha_D^{MAX})$, where (α_D^{MAX}) is a maximal diffraction angle. Because there are generally no theoretical limitations on α_D^{MAX} (apart from a requirement that its absolute value is smaller than 90°), it may be selected according to any practical considerations, such as cost, availability or geometrical limitations which may be imposed by a certain miniaturization necessity. Hence, in one embodiment, further referred to herein as the "at least one hop" embodiment, α_D^{MAX} is selected so as to allow at least one reflection within a predetermined distance x which may vary from about 30 mm to about 80 mm.

For example, for a glass substrate, with an index of refraction of $n_S = 1.5$ and a thickness of 2 mm, a single total internal reflection event of a light having a wavelength of 465 nm within a distance x of 34 mm, corresponds to $\alpha_D^{MAX} = 83.3°$.

In another embodiment, further referred to herein as the "flat" embodiment, α_D^{MAX} is selected so as to reduce the number of reflection events within the substrate, *e.g.*, by imposing a requirement that all the diffraction angles will be sufficiently small, say, below 80°.

In an additional embodiment, particularly applicable to those situations in the industry in which the refraction index of the substrate is already known (for example when device **10** is intended to operate synchronically with a given device which includes a specific substrate), Equation 13 may be inverted to obtain the value of p hence also the value of $\alpha_D^{MAX} = \sin^{-1} p$.

As stated, device **10** can transmit light having a plurality of wavelengths. According to a preferred embodiment of the present invention, for a multicolor image the gratings period is preferably selected to comply with Equation 12, for the shortest wavelength, and with Equation 13, for the longest wavelength. Specifically:

$$\lambda_R/(n_S\, p) \le D \le \lambda_B\,, \qquad \text{(EQ. 14)}$$

where λ_B and λ_R are, respectively, the shortest and longest wavelengths of the multicolor spectrum. Note that it follows from Equation 12 that the index of refraction of the substrate should satisfy, under these conditions, $n_S\, p \ge \lambda_R/\lambda_B$.

The grating period can also be smaller than the sum $\lambda_B + \lambda_R$, for example:

$$D = \frac{\lambda_B + \lambda_R}{n_S \sin(\alpha_D^{MAX}) + n_A}. \qquad \text{(EQ. 15)}$$

According to an additional aspect of the present invention there is provided a apparatus **100** for providing an image to a user in a wide field-of-view.

Reference is now made to Figure 11 which is a schematic illustration of system **300**, which, in its simplest configuration, comprises optical relay device **10** for transmitting image **34** into first eye **25** and second eye **30** of the user, an image generating apparatus, which can be, for example, apparatus **100** as described above or a modification thereof as described hereinunder and a projection element or collimator **44**. Apparatus **100** provides optical relay device **10** with a light beam modulated to constitute the image.

Image generating apparatus **100** can be either analog or digital. An analog image generating apparatus typically comprises a light source **327** and at least one image carrier **29**. Representative examples for light source **327** include, without limitation, a lamp (incandescent or fluorescent), one or more LEDs or OLEDs, and the like. Representative examples for image carrier **29** include, without limitation, a miniature slide, a reflective or transparent microfilm and a hologram.

The light source can be positioned either in front of the image carrier (to allow reflection of light therefrom) or behind the image carrier (to allow transmission of light therethrough). Optionally and preferably, apparatus **100** comprises a miniature CRT. Miniature CRTs are known in the art and are commercially available, for example, from Kaiser Electronics, a Rockwell Collins business, of San Jose, California.

A digital image generating apparatus can comprise passive display panel **330** such as modulator **100** described above, which modulates light emitted from source **327**.

Light sources suitable for a digital image generating system include, without limitation, a lamp (incandescent or fluorescent), one or more LEDs (*e.g.*, red, green and blue LEDs) or OLEDs, and the like. Suitable passive display panels include, without limitation, rear-illuminated transmissive or front-illuminated reflective LCD, Digital Light Processing™ (DLP™) units, and the like. Transparent miniature LCDs are commercially available, for example, from Kopin Corporation, Taunton, Massachusetts. Reflective LCDs are are commercially available, for example, from Brillian Corporation, Tempe, Arizona. Miniature OLED arrays are commercially available, for example, from eMagin Corporation, Hopewell Junction, New York.

DLP™ units are commercially available, for example, from Texas Instruments DLP™ Products, Plano, Texas. The pixel resolution of the digital miniature displays varies from QVGA (320 × 240 pixels) or smaller, to WQUXGA (3840 × 2400 pixels).

System **300** is particularly useful for enlarging a field-of-view of devices having relatively small screens. For example, cellular phones and personal digital assistants (PDAs) are known to have rather small on-board displays. PDAs are also known as Pocket PC, such as the trade name iPAQ™ manufactured by Hewlett-Packard Company, Palo Alto, California. The above devices, although capable of storing and downloading a substantial amount of information in a form of single frames or moving images, fail to provide the user with sufficient field-of-view due to their small size displays.

Thus, according to a preferred embodiment of the present invention system **300** comprises a data source **325** which can communicate with apparatus **100** via a data source interface **323**. Any type of communication can be established between interface **323** and data source **325**, including, without limitation, wired communication, wireless communication, optical communication or any combination thereof. Optionally and preferably data source **325** and source interface **323** are operatively associated with wireless transceivers **332** and **334**, respectively, to establish wireless communication thereamongst. Interface **323** is preferably configured to receive a stream of imagery data (*e.g.*, video, graphics, *etc.*) from data source **325** and to input the data into apparatus **100**. Many types or data sources are contemplated. According to a preferred embodiment of the present invention data source **325** is a communication device, such as, but not limited to, a cellular telephone, a personal digital assistant device (PDA) and a portable computer (laptop). Additional examples for data source **325** include, without limitation, television apparatus, portable television device, satellite receiver, video cassette recorder, digital versatile disc (DVD) player, digital moving picture player (*e.g.*, MP4 player), digital camera, video graphic array (VGA) card, and many medical imaging apparatus, *e.g.*, ultrasound imaging apparatus, digital X-ray apparatus (*e.g.*, for computed tomography) and magnetic resonance imaging apparatus.

In addition to the imagery information, data source **325** may generates also audio information. The audio information can be received by interface **323** and provided to the user, using an audio unit **31** (speaker, one or more earphones, *etc.*).

According to various exemplary embodiments of the present invention, data source **325** provides the stream of data in an encoded and/or compressed form. In these embodiments, system **300** further comprises a decoder **33** and/or a decompression unit **35** for decoding and/or decompressing the stream of data to a format which can be recognized by apparatus **100**. Decoder **33** and decompression unit **35** can be supplied as two separate units or an integrated unit as desired.

System **300** preferably comprises a controller **37** for controlling the functionality of apparatus **100** and, optionally and preferably, the information transfer between data source **325** and apparatus **100**. Controller **37** can control any of the display characteristics of apparatus **100**, such as, but not limited to, brightness, hue, contrast, pixel resolution and the like. Additionally, controller **37** can transmit signals to data source **325** for controlling its operation. More specifically, controller **37** can activate, deactivate and select the operation mode of data source **325**. For example, when data source **325** is a television apparatus or being in communication with a broadcasting station, controller **37** can select the displayed channel; when data source **325** is a DVD or MP4 player, controller **37** can select the track from which the stream of data is read; when audio information is transmitted, controller **37** can control the volume of audio unit **31** and/or data source **325**.

System **300** or a portion thereof (*e.g.*, device **10**) can be integrated with a wearable device, such as, but not limited to, a helmet or spectacles, to allow the user to view the image, preferably without having to hold optical relay device **10** by hand.

Alternatively system **300** or a portion thereof can be adapted to be mounted on an existing wearable device. For example, in one embodiment device **10** is manufactured as a spectacles clip which can be mounted on the user's spectacles, in another embodiment, device **10** is manufactured as a helmet accessory which can be mounted on a helmet's screen.

The present embodiments can also be provided as add-ons to the data source or any other device capable of transmitting imagery data. Additionally, the present embodiments can also be used as a kit which includes the data source, the image generating system, the binocular device and optionally the wearable device. For example, when the data source is a communication device, the present embodiments can be used as a communication kit.

Additional objects, advantages and novel features of the present invention will become apparent to one ordinarily skilled in the art upon examination of the following examples, which are not intended to be limiting. Additionally, each of the various embodiments and aspects of the present invention as delineated hereinabove and as claimed in the claims section below finds experimental support in the following examples.

EXAMPLES

Reference is now made to the following examples, which together with the above descriptions illustrate the invention in a non limiting fashion.

EXAMPLE 1

Diffraction of Red Light

Following is a non-limiting example in which planar dimension calculations are performed in accordance with the teachings of the preferred embodiments of the invention for the diffraction of red light.

The present calculations are for 509 nm period gratings formed in a light transmissive substrate having index of refraction of 1.522 and thickness of 2 mm. As a representative example for red light, a wavelength of 615 nm was assumed.

With the above values of the grating period, index of refraction and wavelength a horizontal field-of-view Ω_y of [−12.0°, +12.0°] and a vertical field-of-view Ω_x of [−9.0°, +9.0°] can be achieved. The overall (diagonal) field-of-view Ω is calculated using Equation 5 to obtain $\Omega = [-15°, +15°]$.

For $\Delta z = 25$ mm, the minimal dimensions of the output optical element(s) are (see Equation 6) $L_{O,\ min} = 10.6$ mm and $W_{O,\,min} = 7.9$ mm. For $L_{EB} = 4$ mm, $W_{EB} = 1$ mm and $O_p = 3$ mm, the dimensions of the output optical element(s) are (see Equation 7) $L_O = 17.6$ mm and $W_O = 11.9$ mm.

Using the thickness of the substrate and the above values of Ω_y one obtains a hop-length of $h = 3.5$ mm which is then used to set the length L_I of the input element to be from about 3.5 mm to about 10.5 mm.

The above values of Ω_x and Ω_y correspond to an outermost propagation angle (as projected on the x-y plane) of ±8.8°. Thus, in accordance with preferred embodiments of the present invention, the value of the angular parameter γ is 8.8°.

For $\Delta y = 17.7$ mm, and $L_I = 10$ mm, the width W_I of the input optical element is (see Equation 8) is $W_I = 22.8$ mm.

EXAMPLE 2

Diffraction of Blue Light

Following is a non-limiting example in which planar dimension calculations are performed in accordance with the teachings of the preferred embodiments of the invention for the diffraction of blue light.

The present calculations are for 389 nm period gratings formed in a light transmissive substrate having index of refraction of 1.529 and thickness of 1.8 mm. As a representative example for blue light, a wavelength of 465 nm was assumed.

With the above values of the grating period, index of refraction and wavelength a horizontal field-of-view Ω_y of $[-11°, +11°]$ and a vertical field-of-view Ω_x of $[-8.3°, +8.3°]$ can be achieved. The overall (diagonal) field-of-view Ω is calculated using Equation 5 to obtain $\Omega = [-13.7°, +13.7°]$.

For $\Delta z = 20$ mm, the minimal dimensions of the output optical element(s) are $L_{O,\,min} = 7.8$ mm and $W_{O,\,min} = 5.8$ mm. For $L_{EB} = 5$ mm, $W_{EB} = 2$ mm and $O_p = 3$ mm the dimensions of the output optical element(s) are $L_O = 15.8$ mm and $W_O = 10.8$ mm.

Using the thickness of the substrate and the above values of Ω_y one obtains a hop-length of $h = 3.1$ mm, which is then used to set the length L_I of the input element to be from about 3 mm to about 10 mm.

The above values of Ω_x and Ω_y correspond to an outermost propagation angle (as projected on the x-y plane) of $\pm 8°$, hence $\gamma = 8°$, in accordance with preferred embodiments of the present invention.

For $\Delta y = 16.6$ mm and $L_I = 9$ mm, the width W_I is 19.9 mm.

It is appreciated that certain features of the invention, which are, for clarity, described in the context of separate embodiments, may also be provided in combination in a single embodiment. Conversely, various features of the invention,

which are, for brevity, described in the context of a single embodiment, may also be provided separately or in any suitable subcombination.

Although the invention has been described in conjunction with specific embodiments thereof, it is evident that many alternatives, modifications and variations will be apparent to those skilled in the art. Accordingly, it is intended to embrace all such alternatives, modifications and variations that fall within the spirit and broad scope of the appended claims. All publications, patents and patent applications mentioned in this specification are herein incorporated in their entirety by reference into the specification, to the same extent as if each individual publication, patent or patent application was specifically and individually indicated to be incorporated herein by reference. In addition, citation or identification of any reference in this application shall not be construed as an admission that such reference is available as prior art to the present invention.

WHAT IS CLAIMED IS:

1. Apparatus for providing light, comprising:

a light source having a light emitting surface for generating a light beam;

a passive modulator positioned in the optical path of said light beam and configured to modulate said light beam to constitute an image therein; and

at least one linear focusing element defining a longitudinal optical axis and being designed and constructed to form a first linear focus with respect to a first transverse dimension at a first longitudinal location along said longitudinal optical axis, and a second linear focus with respect to a second transverse dimension at a second longitudinal location along said longitudinal optical axis.

2. The apparatus of claim 1, wherein said at least one linear focusing element comprises a first arrangement of lenses characterized by spherical symmetry, and a second arrangement of lenses characterized by a symmetry other than spherical symmetry.

3. The apparatus of claim 1, wherein said first location is at a distance Z_1 from said light source and said second location is at a distance Z_2 from said light source, and wherein the ratio between Z_2 and Z_1 is at least 2.

4. Apparatus for providing light, comprising:

a light source having a light emitting surface for generating a light beam;

a passive modulator positioned in the optical path of said light beam and configured to modulate said light beam to constitute an image therein; and

at least one linear focusing element defining a longitudinal optical axis and having a first arrangement of lenses characterized by spherical symmetry and a second arrangement of lenses characterized by a symmetry other than spherical symmetry.

5. A method of providing light, comprising operating the apparatus of any of claims 1 to 4.

6. The apparatus or method of claim 1, 4 or 5, wherein the apparatus further comprises an optical projection element interposed in the light path of said light beam and configured for projecting said light beam in a collimated manner.

7. The apparatus or method of claim 1, 4 or 5, wherein said at least one linear focusing element is designed and constructed such as to form an intermediate virtual image of a first linear segment of said light emitting surface, and a real image of said intermediate virtual image at said first longitudinal location.

8. The system of claim 6, wherein said at least one linear focusing element is designed and constructed such as to form an intermediate virtual image of a second linear segment of said light emitting surface, and wherein said projection optical element is designed and constructed such as to form real image of said intermediate virtual image at said second longitudinal location.

9. A system for providing an image to a user, comprising:

an image generating apparatus which comprises a light source having a light emitting surface for generating a light beam, a passive modulator positioned in the optical path of said light beam and configured to modulate said light beam to constitute an image therein, and a optical projection element for projecting said light beam in a collimated manner; and

an optical relay device for relaying said light beam in a manner such that said light beam is expanded in a first transverse dimension and relayed to occupy at least one predetermined two-dimensional eye-box region in space;

said image generating apparatus being designed and constructed to form a first linear focus of said light source at said projection optical element and a second linear focus of said light source at said eye-box region, wherein said first linear focus is with respect to said first transverse dimension and said second linear focus is with respect to said second transverse dimension.

10. The apparatus, method or system of claim 1, 4, 5 or 9, wherein said first linear focus is formed at a first transverse plane being at said first longitudinal location, and wherein any point on said first transverse plane other than points

belonging to said first linear focus is out of focus with respect to said light emitting surface.

11. The apparatus, method or system of claim 7, wherein said second linear focus is formed at a second transverse plane being at said second longitudinal location, and wherein any point on said second transverse plane other than points belonging to said second linear focus is out of focus with respect to said light emitting surface.

12. The system of claim 9, wherein said optical relay device comprises a light transmissive substrate formed with at least one input optical element for coupling said light beam into said light transmissive substrate, and at least one output optical element for expanding said light beam in said first transverse dimension and coupling said light beam out of said light transmissive substrate to said two-dimensional region.

13. The system of claim 12, wherein said at least one input optical element and/or said at least one output optical element comprise diffractive optical elements.

14. The system of claim 9, wherein said at least one linear focusing element comprises a first arrangement of lenses characterized by spherical symmetry and a second arrangement of lenses characterized by a symmetry other than spherical symmetry.

15. The apparatus, method or system of claim 2, 4, 5 or 9, wherein said second arrangement of lenses is characterized by cylindrical symmetry.

16. The system of claim 13, wherein said optical relay device comprises an input diffractive optical element, a first output diffractive optical element and a second output diffractive optical element;

said input diffractive optical element being designed and constructed for diffracting said light beam to propagate within said light-transmissive substrate via total internal reflection;

said first output diffractive optical element is designed and constructed for diffracting light corresponding to a first part of said image out of said light-transmissive substrate; and

said second output diffractive optical element is designed and constructed for diffracting light corresponding to a second part of said image out of said light-transmissive substrate, such that the combination of said first and said second part substantially reconstructs said image.

17. The system of claim 12, wherein each of said at least one input optical element and said at least one output optical element is characterized by planar dimensions defined by a length along said first transverse dimension and a width along said second transverse direction, wherein a width of said at least one output optical element is smaller than a width of said at least one input optical element.

18. A method of viewing an image, comprising operating the system of any of claims 9 to 17.

19. The apparatus, method or system of claim 2, 4, 5, 14 or 18, wherein said at least one linear focusing element is characterized by a first effective focal length in said first transverse dimension and a second effective focal length in said second transverse dimension, said second effective focal length being longer than said first effective focal length

20. The system of claim 9, wherein said at least one linear focusing element is designed and constructed such that as to form an intermediate virtual image of a first linear segment of said light emitting surface, and a real image of said intermediate virtual image at said projection optical element.

21. The system of claim 9, wherein said at least one linear focusing element is designed and constructed such as to form an intermediate virtual image of a second linear segment of said light emitting surface, and wherein said projection optical element is designed and constructed such as to form a real image of said intermediate virtual image at said at least one eye-box region.

22. The apparatus, method or system of claim 19, wherein said at least one linear focusing element is a lenslet array.

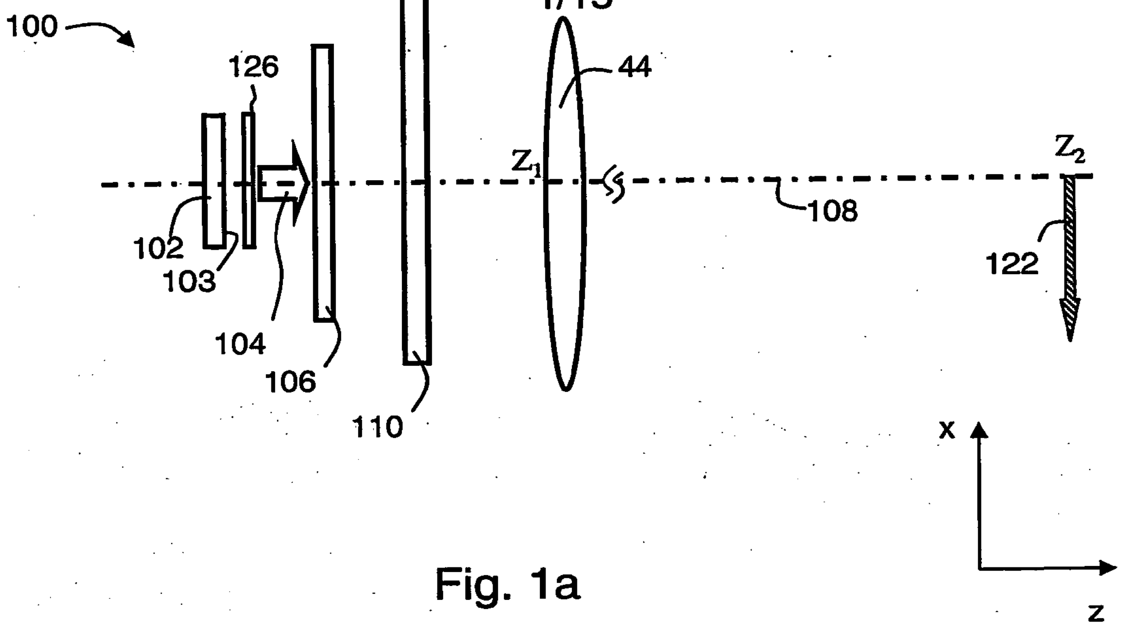
23. The apparatus, method or system of claim 19, wherein said lenslet array has a first side and a second side opposite said first side, wherein said first arrangement of lenses is an array of spherical lenses arranged on said first side, and wherein said second arrangement of lenses is array of cylindrical lenses arranged on said second side.

24. The apparatus, method or system of claim 23, wherein at least one of said array of cylindrical lenses and said array of spherical lenses is corrugated so as to impart a substantially homogenous intensity distribution across said light beam.

25. The apparatus, method or system of claim 19, wherein said lenslet array is made, at least in part, of a diffractive material.

26. The apparatus, method or system of claim 1, 5, 9 or 18, wherein said at least one linear focusing element comprises at least one element selected from the group consisting of a condenser lens system, a Fresnel zone plate and a holographic lens.

27. The apparatus, method or system of claim 1, 4, 5, 9 or 18, wherein the apparatus further comprises beam homogenizer interposed in the optical path of said light beam for imparting a substantially homogenous intensity distribution across said light beam.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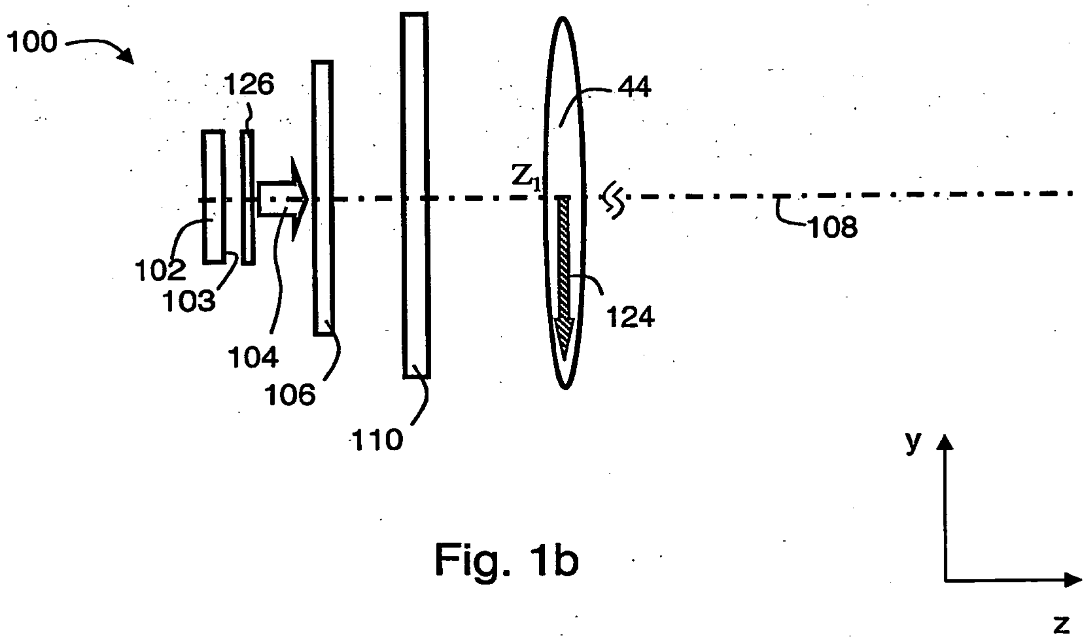
44
Z_1
Z_2
108
102
103
104
106
110
122
x
z

Fig. 1a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126
44
Z_1
108
102
103
104
106
110
124
y
z

Fig. 1b

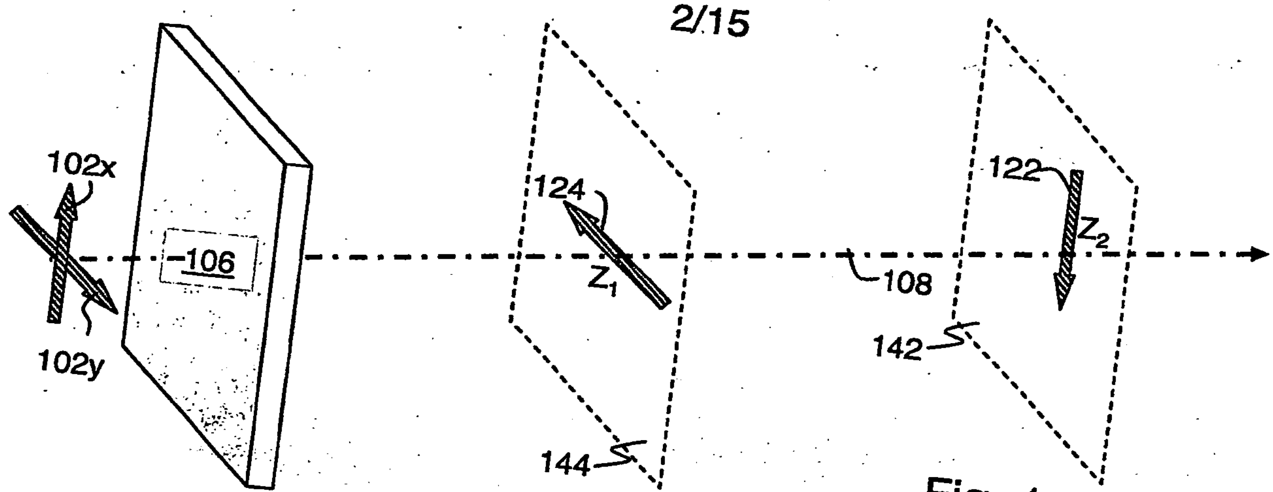


Fig. 1c

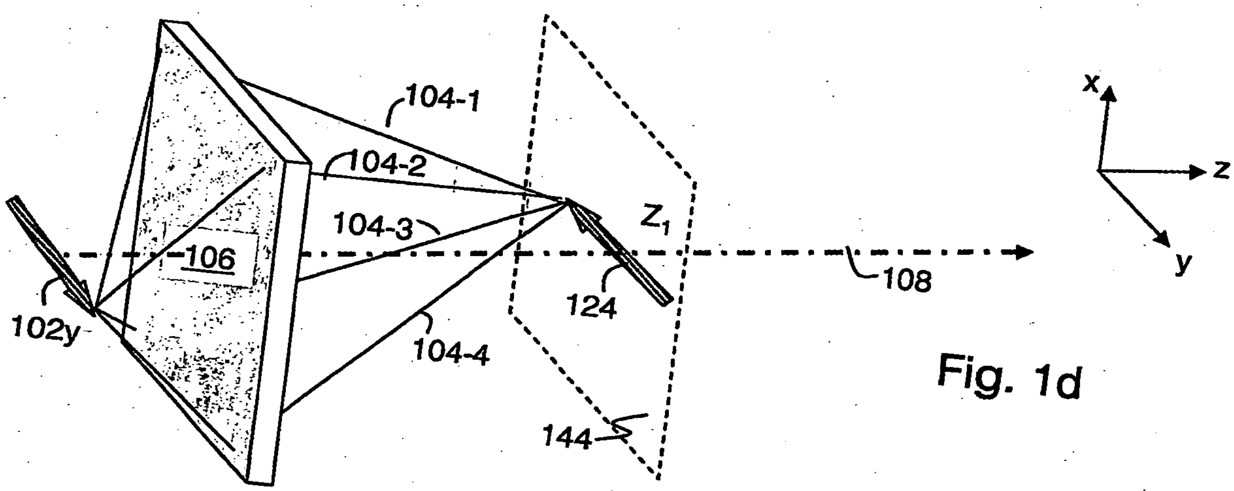


Fig. 1d

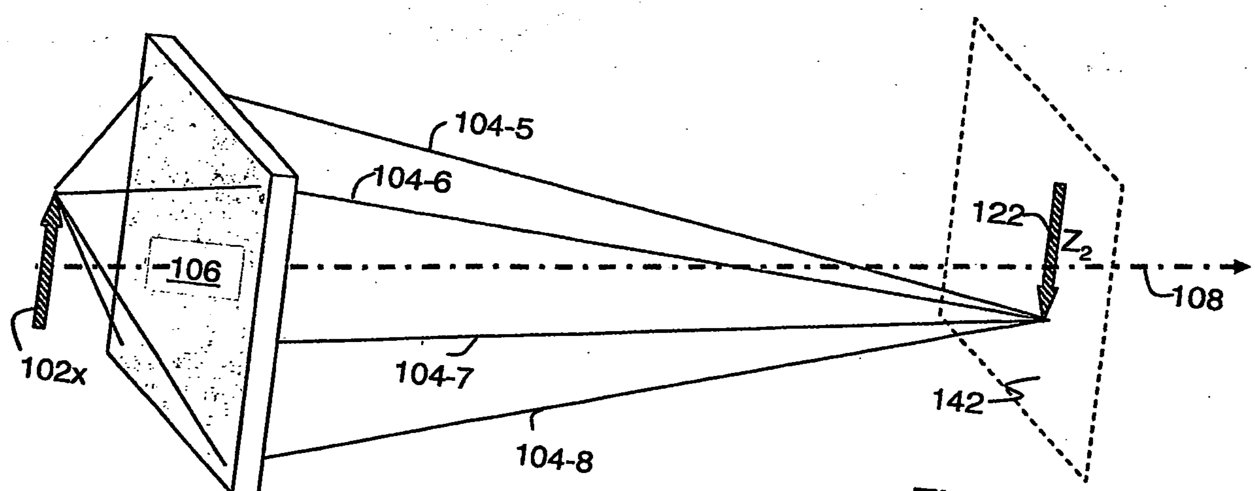


Fig. 1e

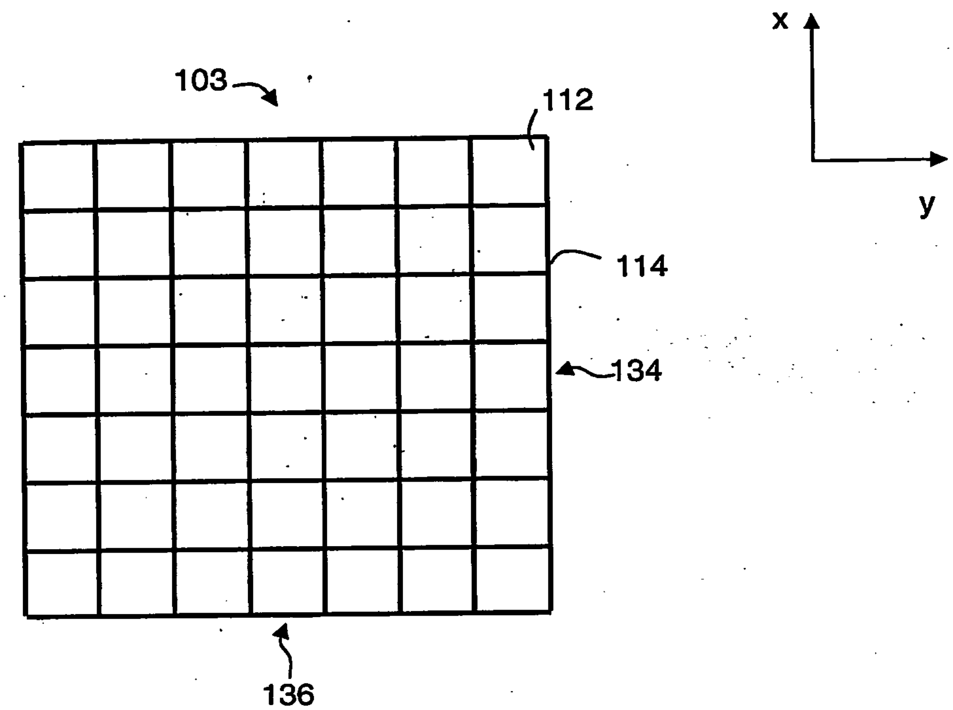


Fig. 2a

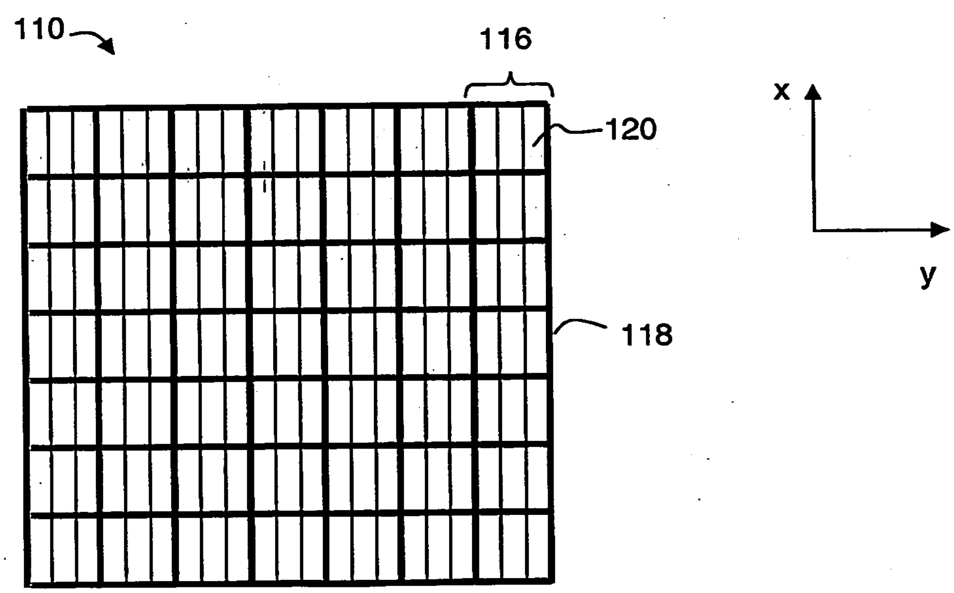


Fig. 2b

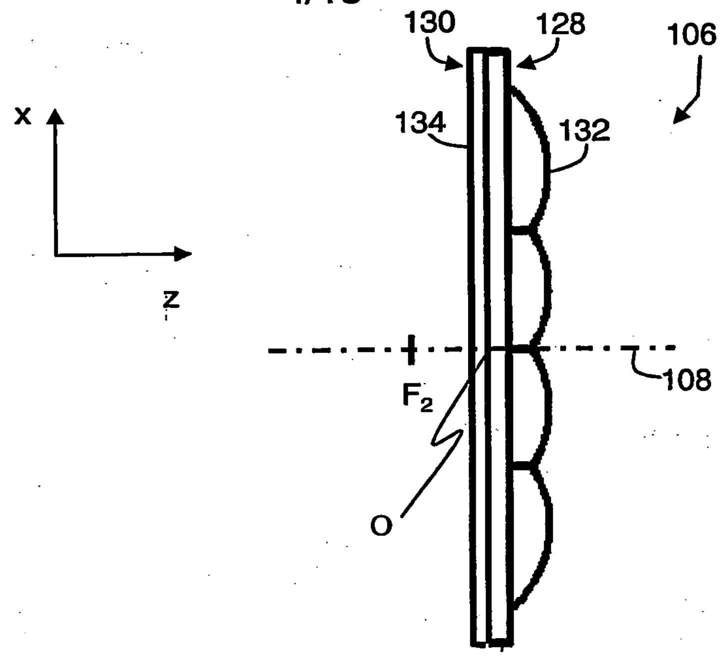


Fig. 3a

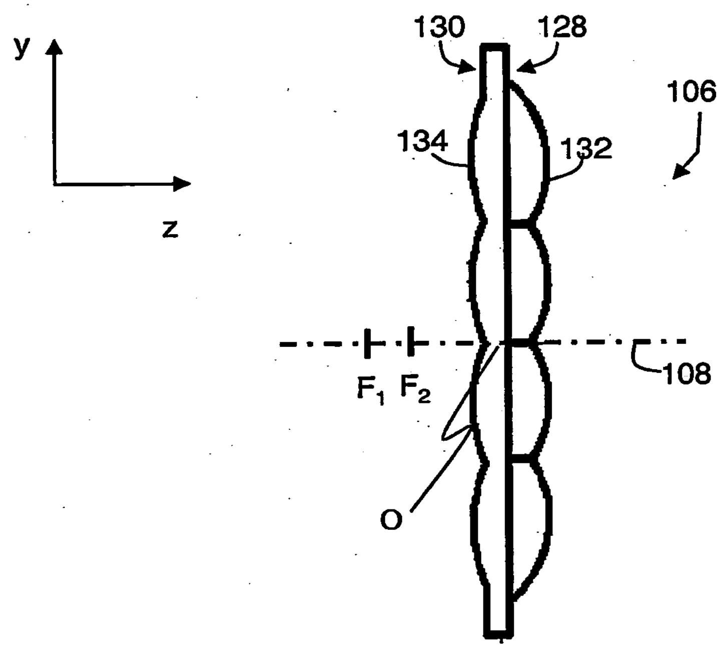


Fig. 3b

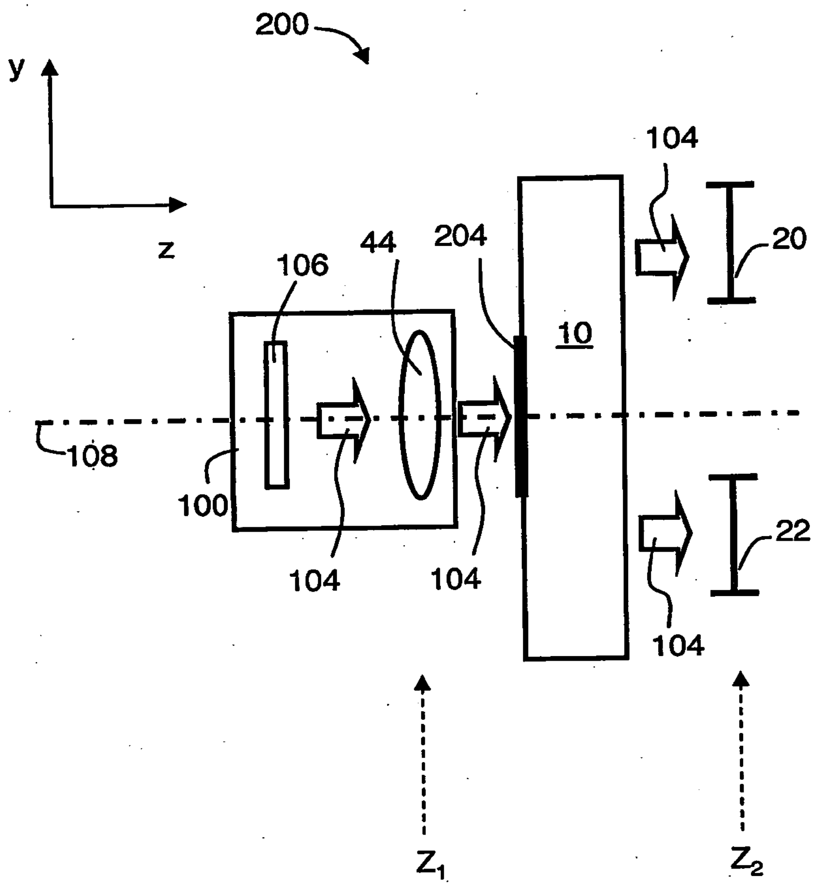


Fig. 4

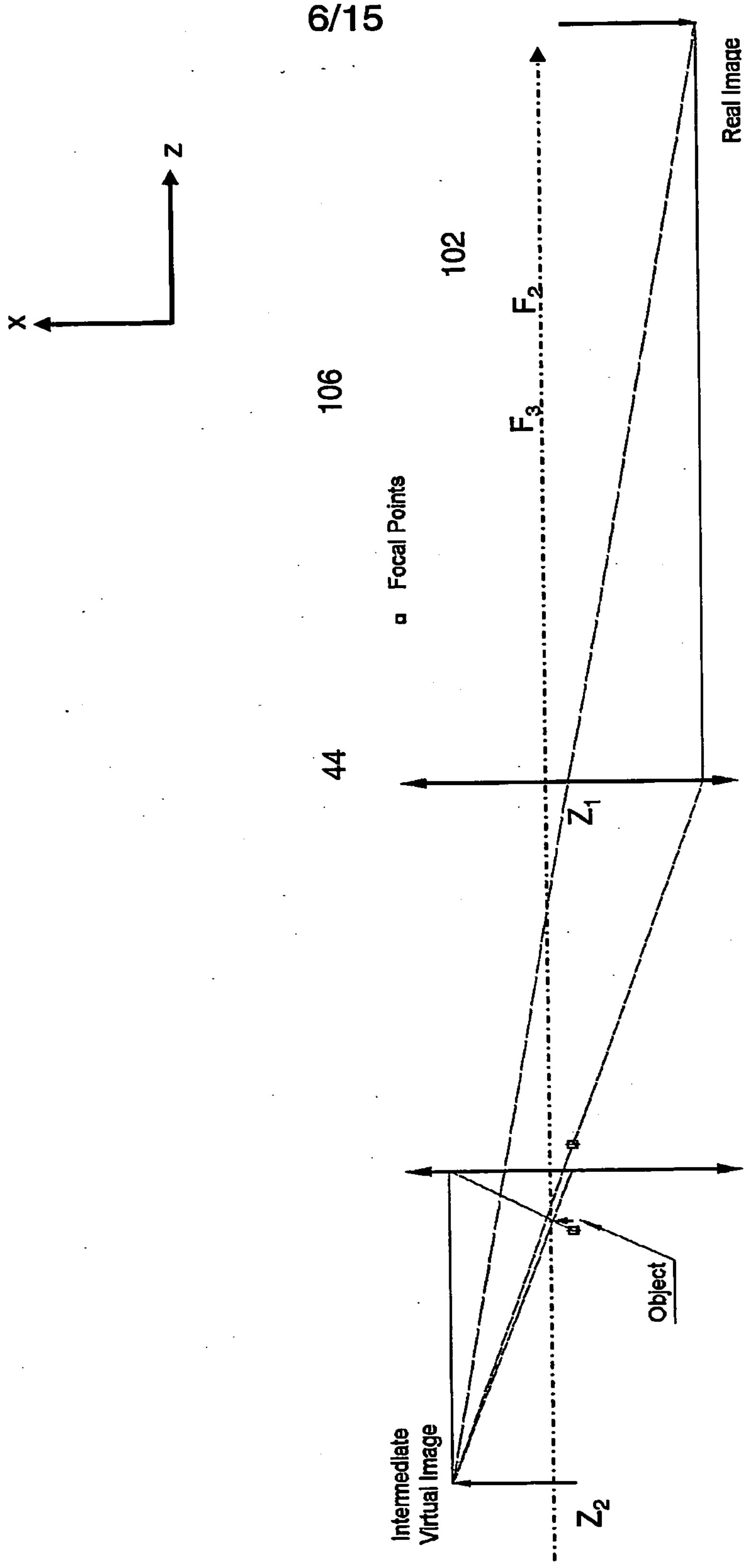

z
x
102
106
F_2
F_3
Focal Points
44
Z_1
Real Image
Object
Intermediate Virtual Image
Z_2

Fig. 5a

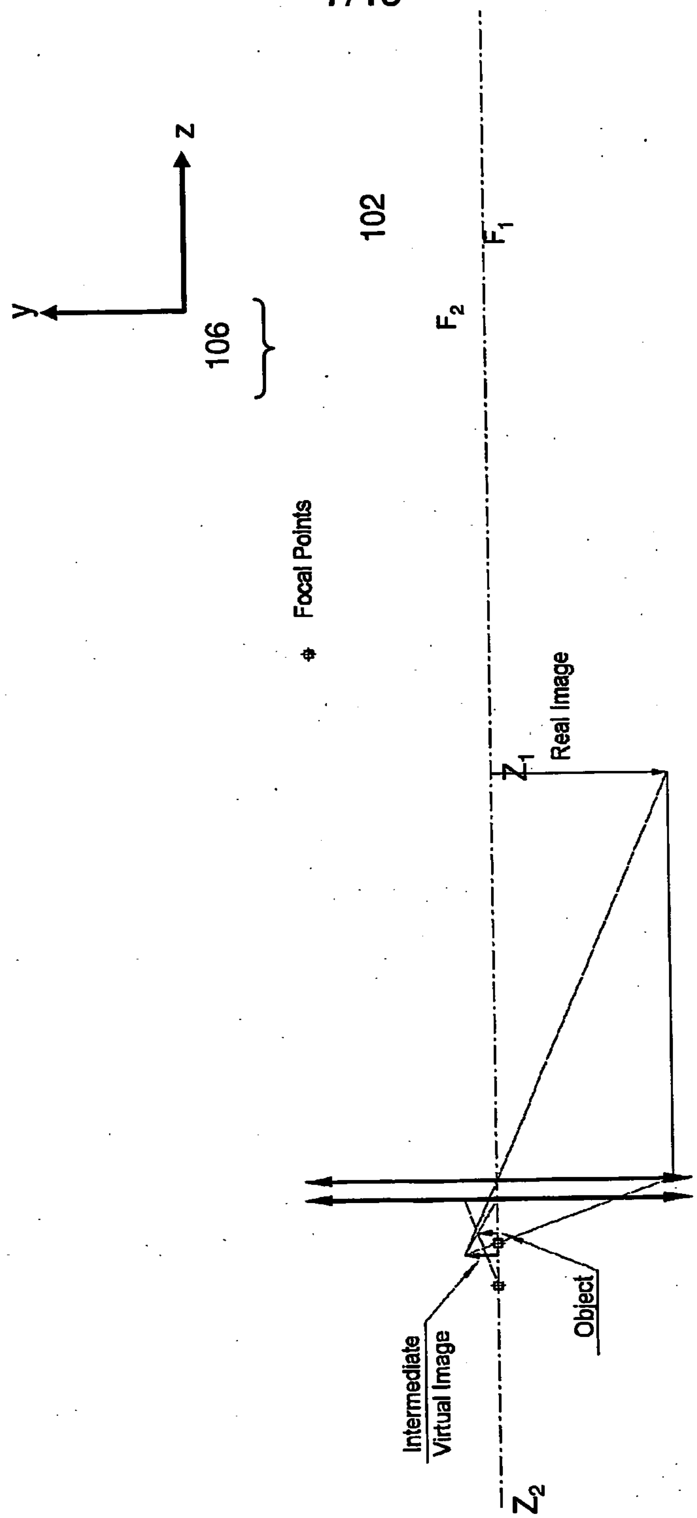
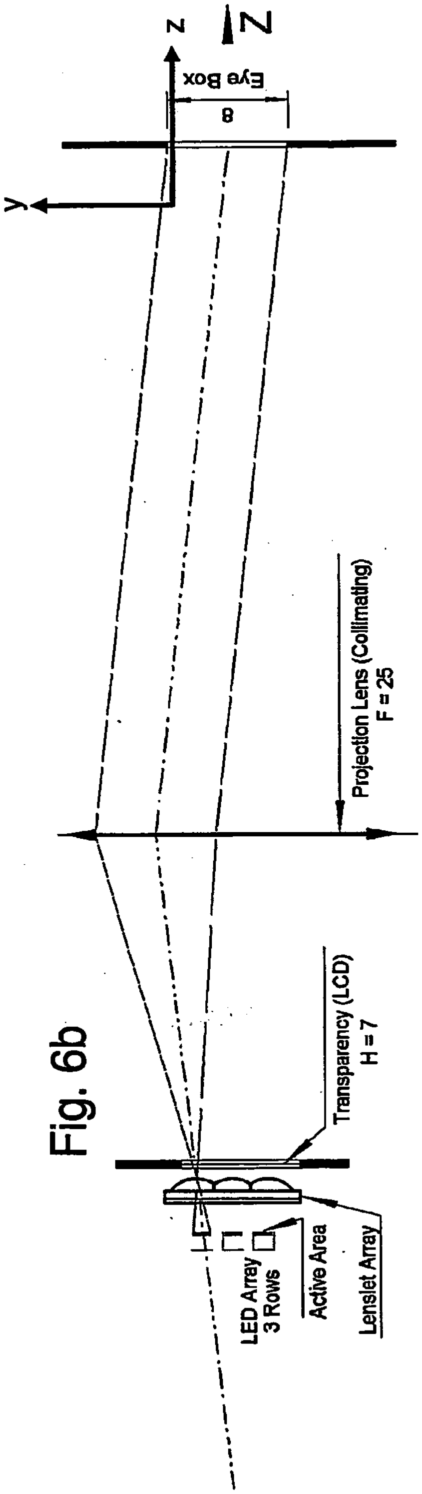
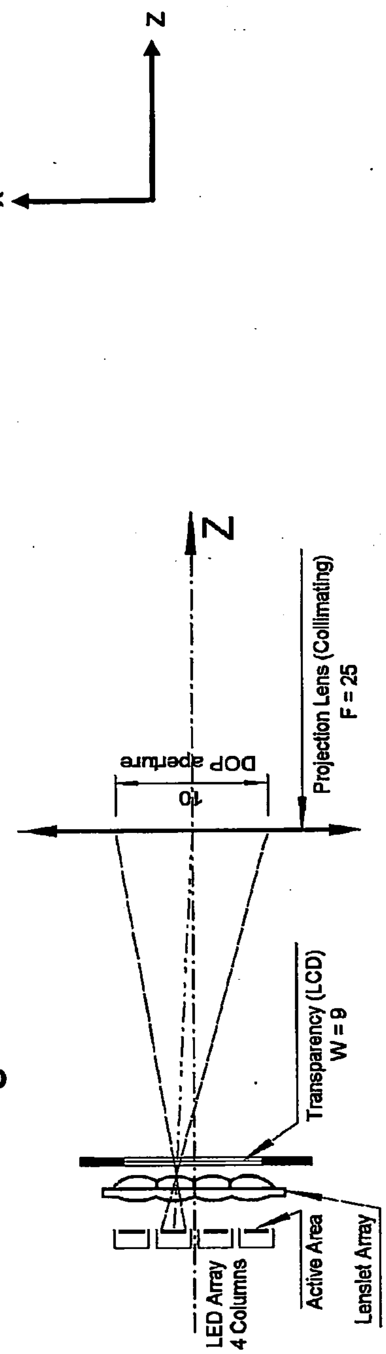

z
y
102
106
F_1
F_2
Focal Points
Real Image
Z_1
Z_2
Intermediate
Virtual Image
Object

Fig. 5b



z
Z
Eye Box
8
y
Projection Lens (Collimating)
F = 25
Transparency (LCD)
H = 7
LED Array
3 Rows
Active Area
Lenslet Array

Fig. 6b



z
x
Z
DOP aperture
10
Projection Lens (Collimating)
F = 25
Transparency (LCD)
W = 9
LED Array
4 Columns
Active Area
Lenslet Array

Fig. 6a

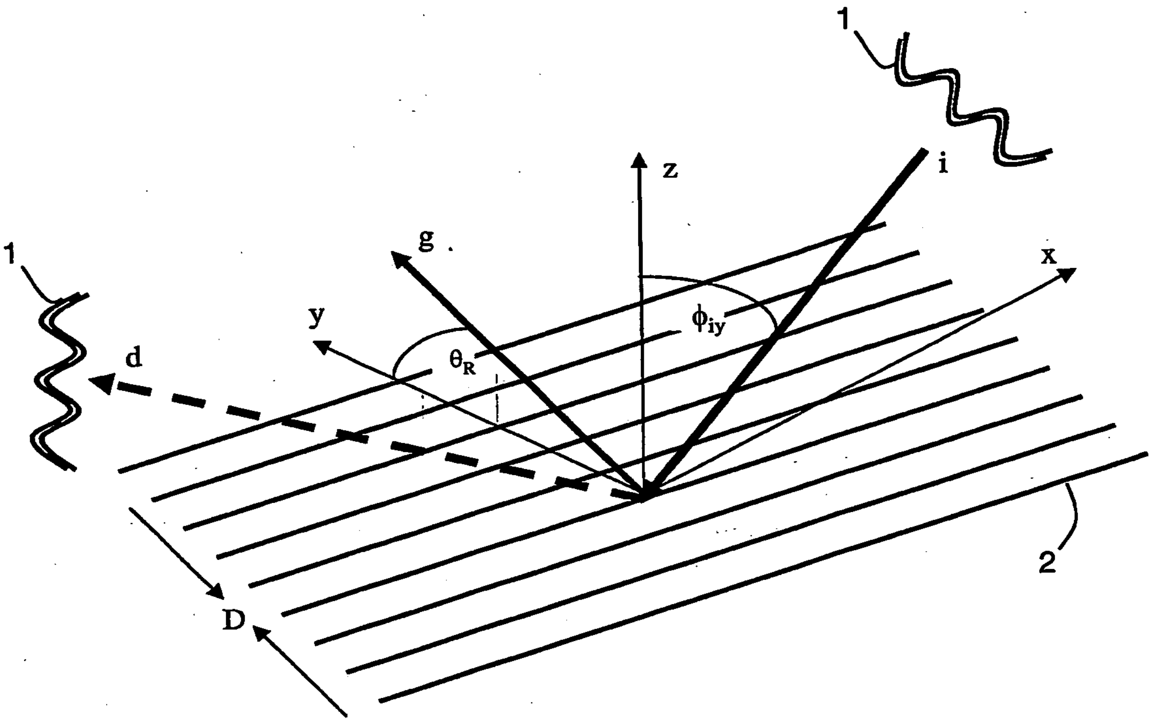
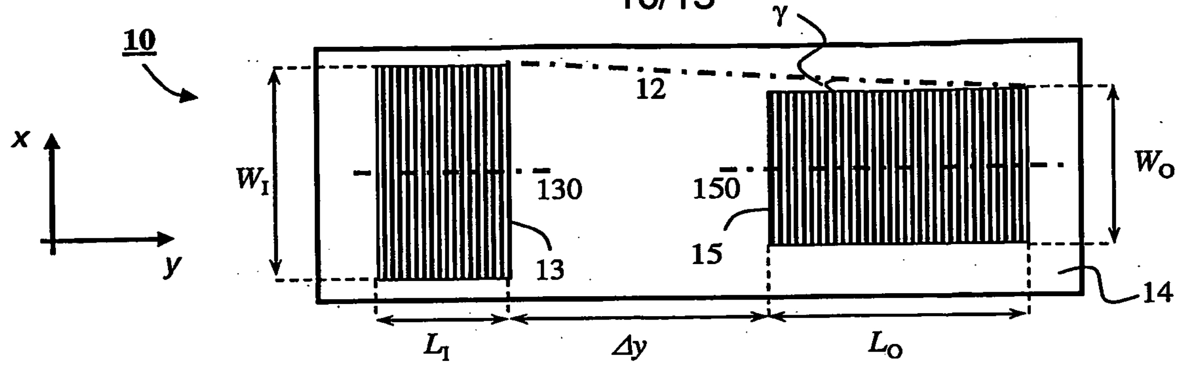


Fig. 7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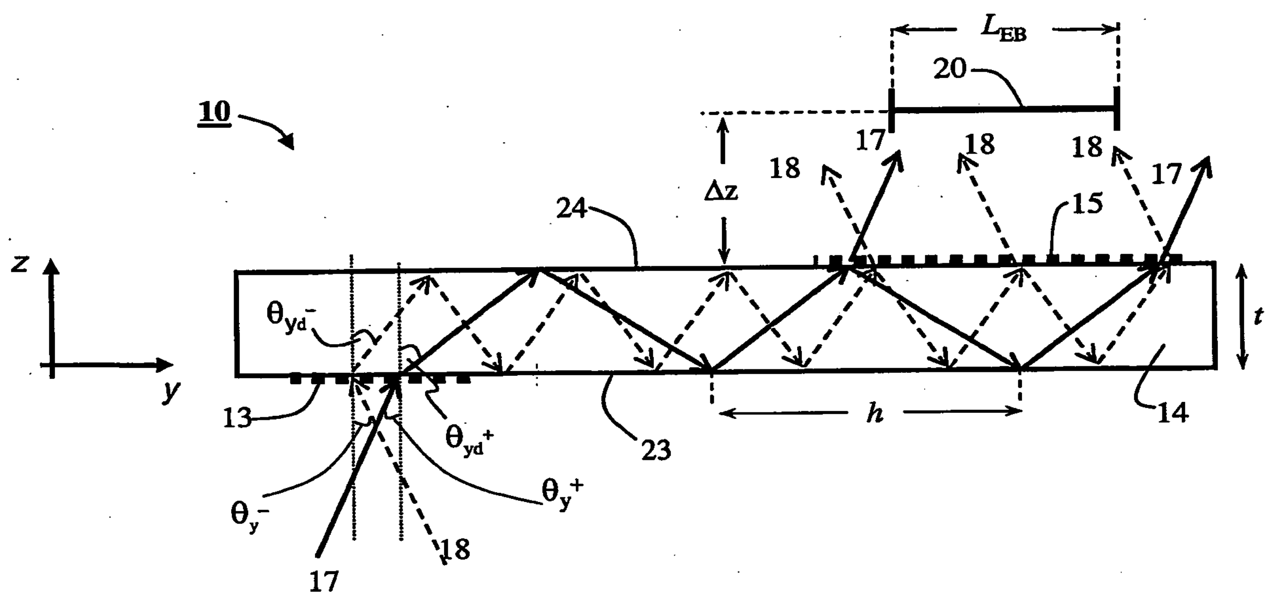
x
y
γ
12
W_I
130
150
W_O
13
15
14
L_I
Δy
L_O

Fig. 8a


L_{EB}
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10
17
18
18
18
17
Δz
24
15
z
y
θ_{yd}^-
t
13
θ_{yd}^+
23
h
14
θ_y^-
θ_y^+
18
17

Fig. 8b

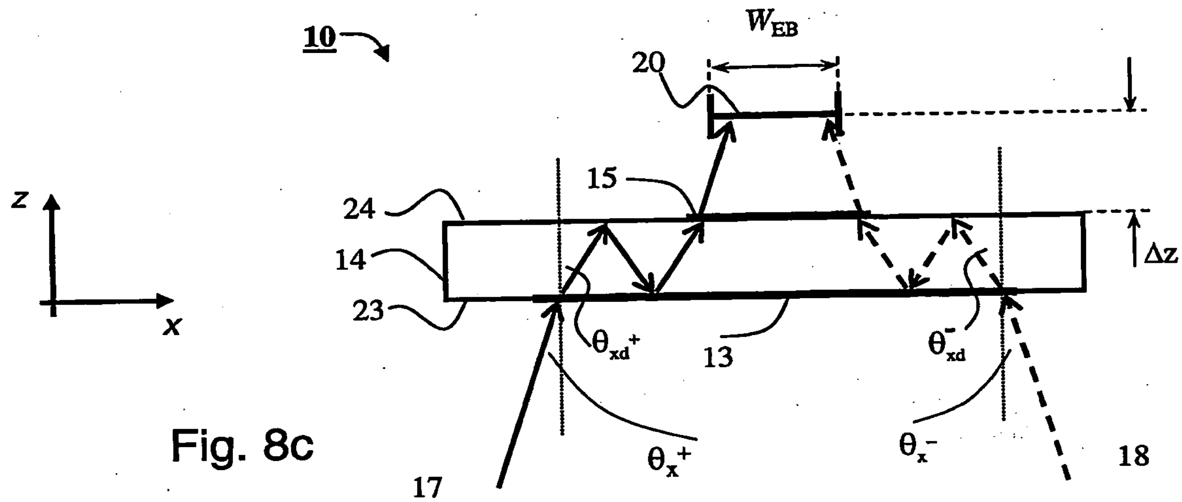


Fig. 8c

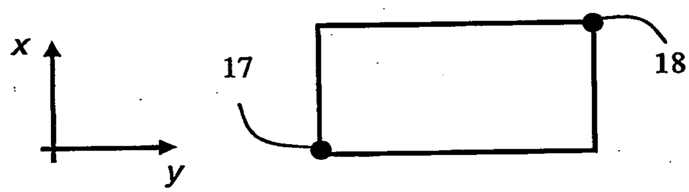


Fig. 8d

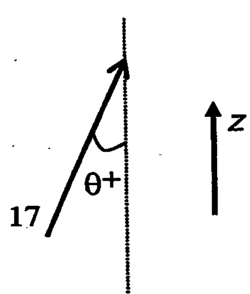


Fig. 8e

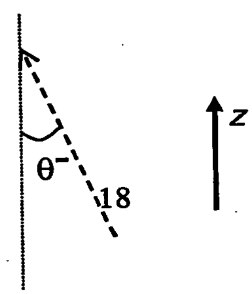


Fig. 8f

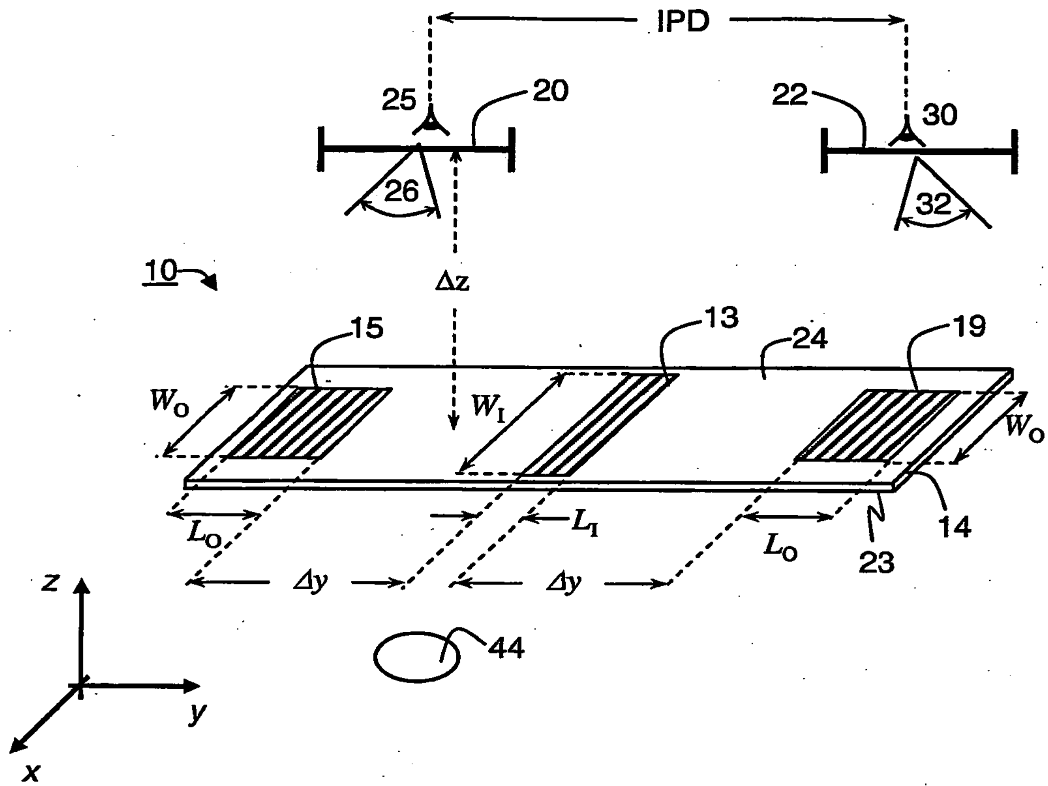
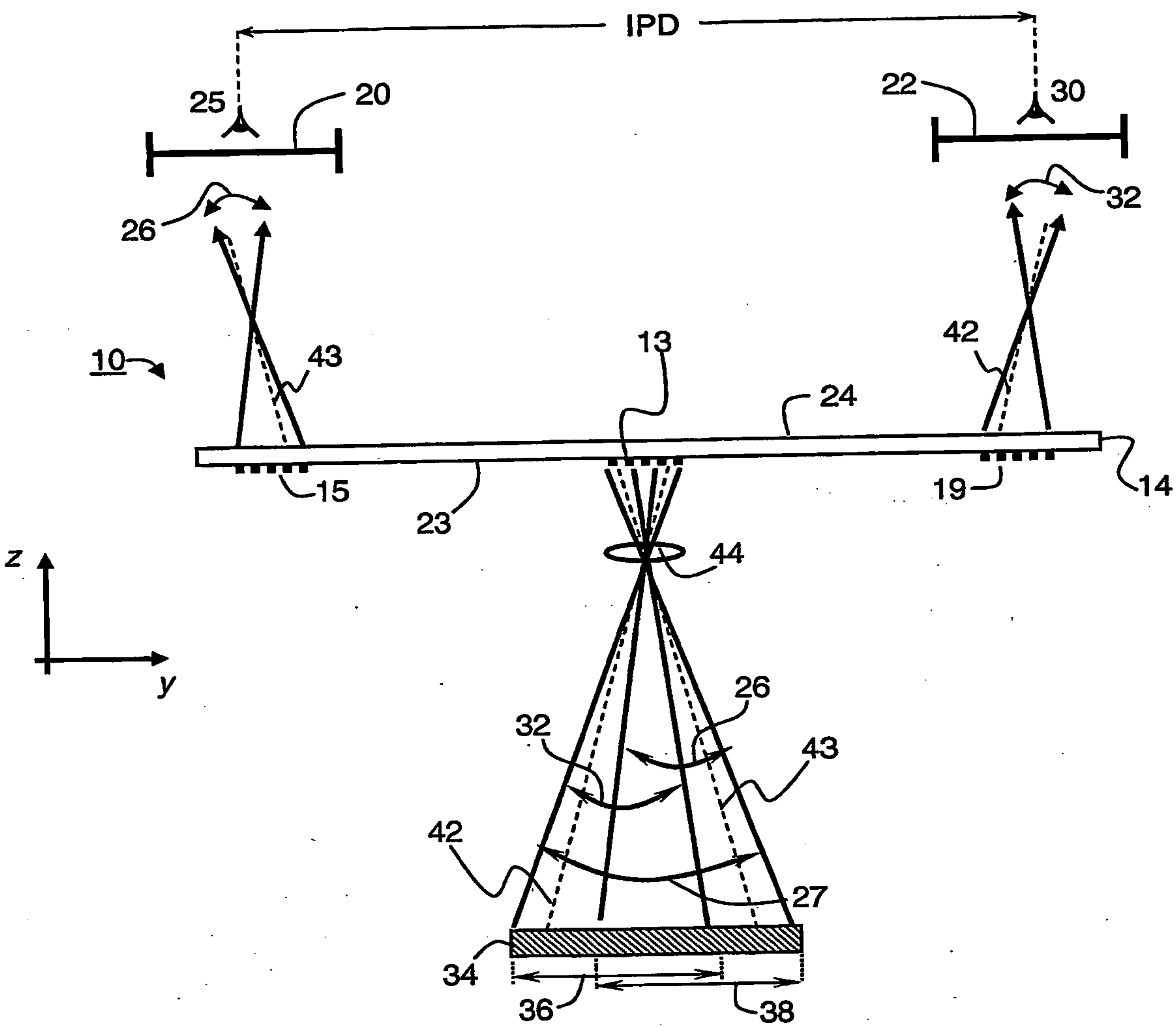

IPD
25
20
22
30
26
32
10
Δz
15
13
24
19
W_O
W_I
W_O
L_O
L_I
L_O
14
23
Δy
Δy
44
z
y
x

Fig. 9a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25
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22
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26
32
10
43
13
42
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23
19
14
44
z
y
26
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43
42
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34
36
38

Fig. 9b

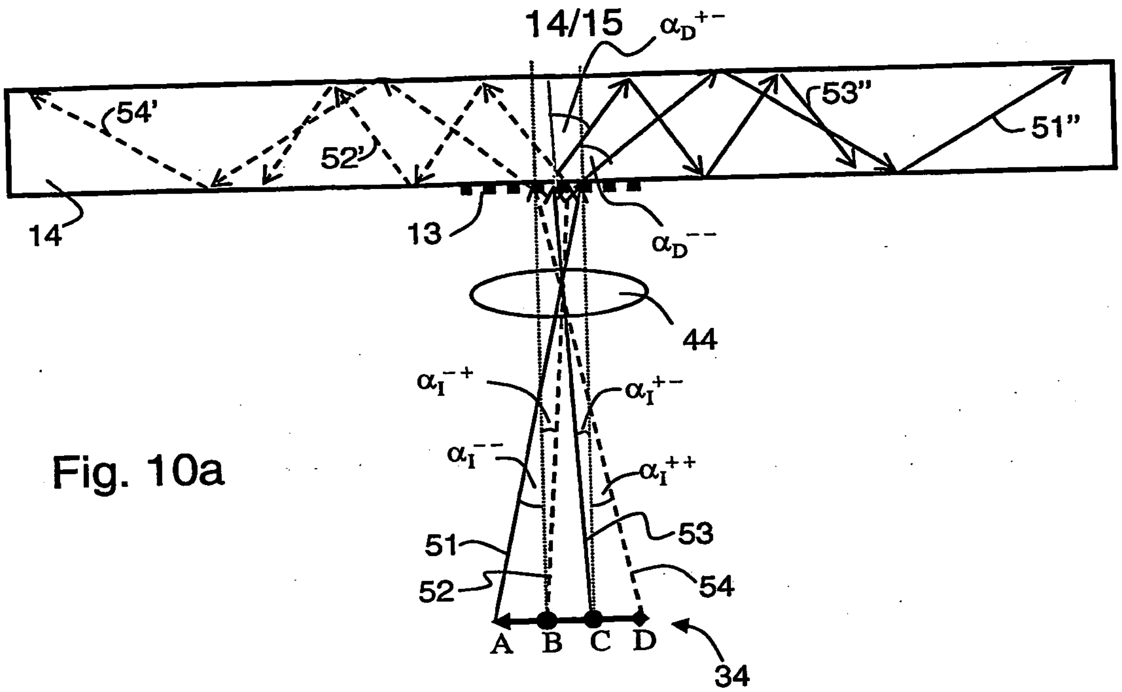

Fig. 10a

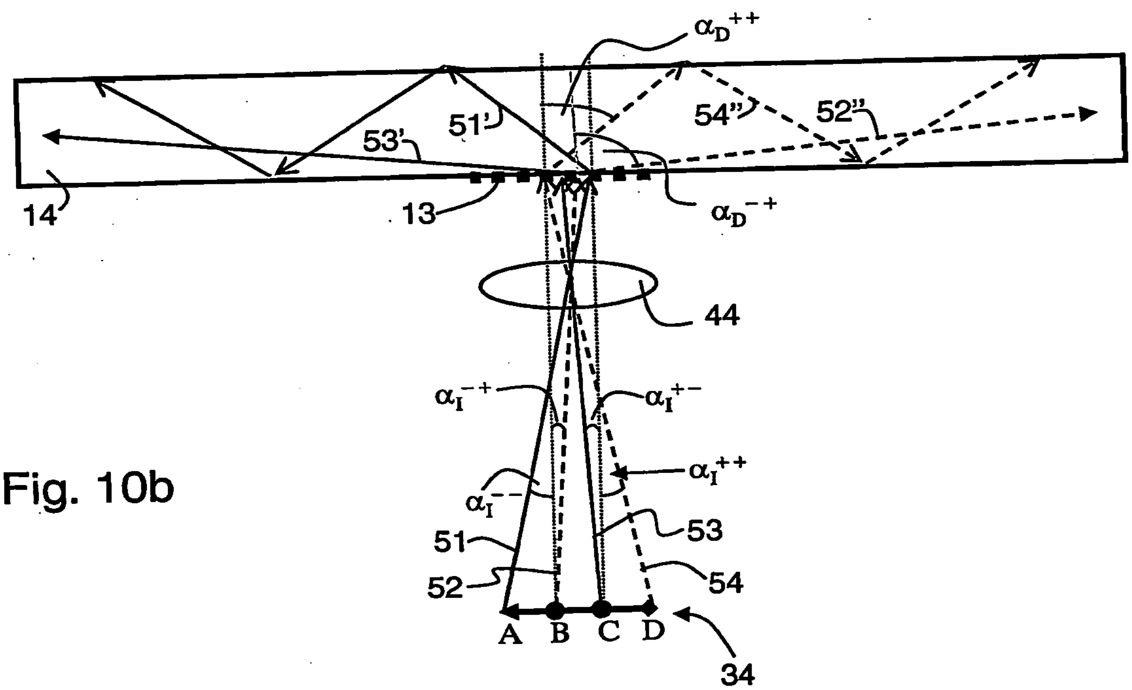

Fig. 10b

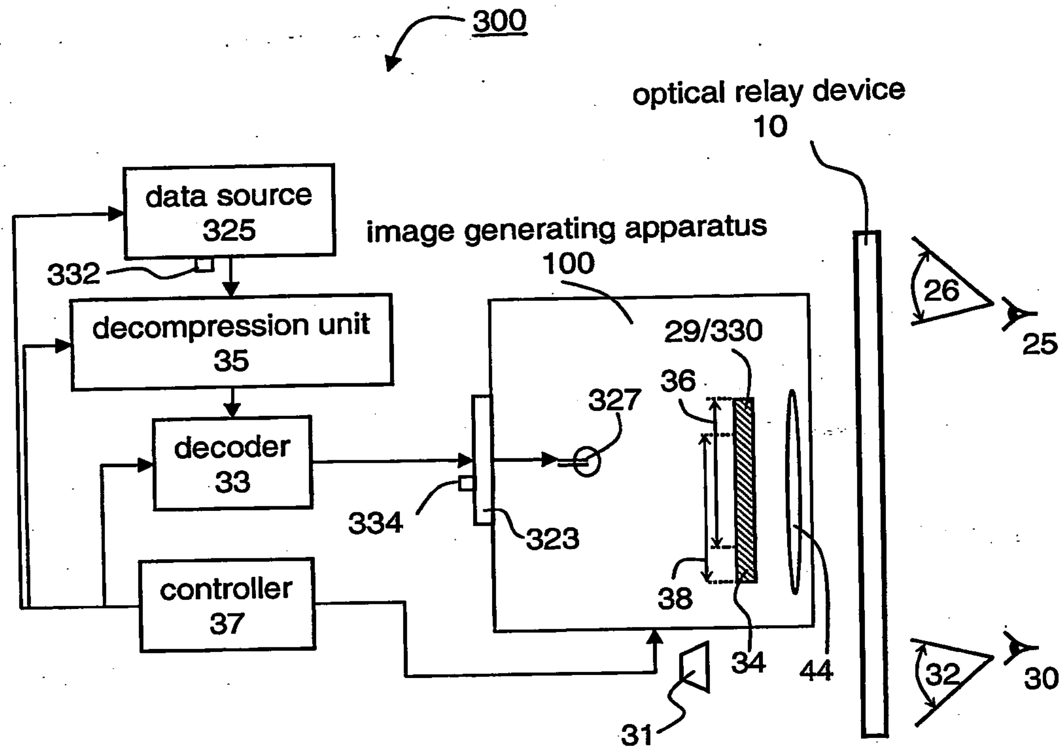
300
optical relay device
10
data source
325
image generating apparatus
100
332
decompression unit
35
29/330
26
25
36
327
decoder
33
334
323
38
controller
37
34
44
32
30
31

Fig. 11

INTERNATIONAL SEARCH REPORT

International application No
PCT/IL2007/000636

A. CLASSIFICATION OF SUBJECT MATTER
INV. H04N5/74 G02B27/09 G02B27/01

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H04N G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 1 333 308 A2 (SAMSUNG ELECTRONICS CO LTD [KR]) 6 August 2003 (2003-08-06) paragraphs [0026] - [0029]; figures 2,7,8,10 paragraphs [0036] - [0039]	1-8
Y		8-18, 22-27
Y	EP 1 577 872 A (SANYO ELECTRIC CO [JP]) 21 September 2005 (2005-09-21) paragraphs [0012], [0013]; figure 1	1-8
Y	EP 1 031 870 A2 (SEIKO EPSON CORP [JP]) 30 August 2000 (2000-08-30) paragraphs [0071] - [0077]; figures 5a,5b	1-8
Y	US 2006/018014 A1 (NIV YEHUDA [IL] ET AL) 26 January 2006 (2006-01-26) paragraphs [0191] - [0207]; figures 2,4,6	9-18, 22-27

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
28 September 2007	08/10/2007

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Hambach, Dirk

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/IL2007/000636

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